Discovery of Neutrino Oscillations the experimental program

L. Labarga, Dept. Física Teórica UAM, 20151215

Outline:

- Neutrino sources
- The discovery of the neutrino / Search for solar neutrinos:
  First hint of massive of neutrinos: "the solar neutrino problem"
- Water-Cherenkov technique; very large amount of mass instrumented
- Super-Kamiokande
  - Discovery of oscillation in atmospheric neutrinos (mainly muon)
  - Precise measurement of solar neutrino deficit
- SNO (Sudbury Neutrino Observatory)
  - Measurement of the whole solar neutrino flux.
  - Discovery of oscillation in solar neutrinos (mainly electron)
- Final remarks

Neutrinos Sources for Experiments:

Sun *many*
Atmosphere *many*

most of this talk about them

Nuclear Power Plants *many*
Particle Acelerators *many*

Center of the Earth *a few*

Supernova *a few* , DSBN
Cosmos *a few*

Relic Neutrino Cosmic Background

Experimental discovery of the ν

Not easy, most relevant ideas by:

Pontecorvo (1948) use reaction
Alvarez (1949) $\nu + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

Discovery by Cowan, Raines 1955:

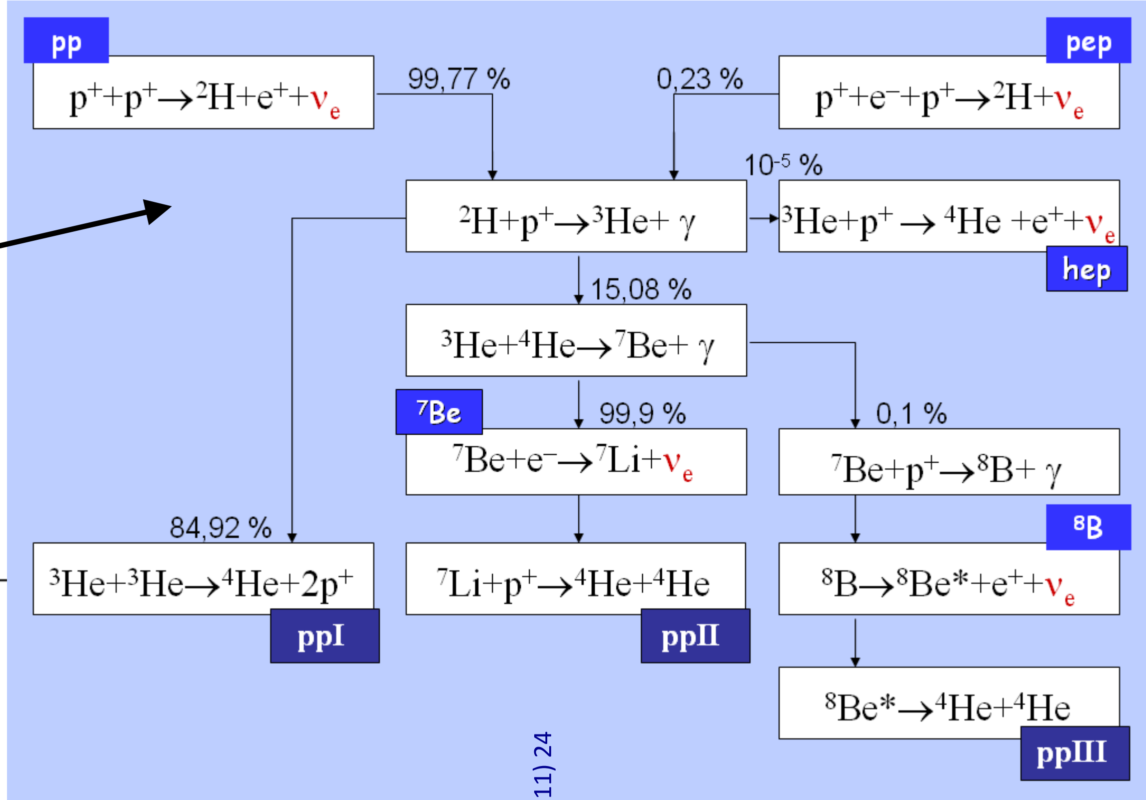
go close to nuclear power reactor
Savannah River in South Carolina
study reaction $\nu + p \rightarrow n + e^-$
delayed coincidence

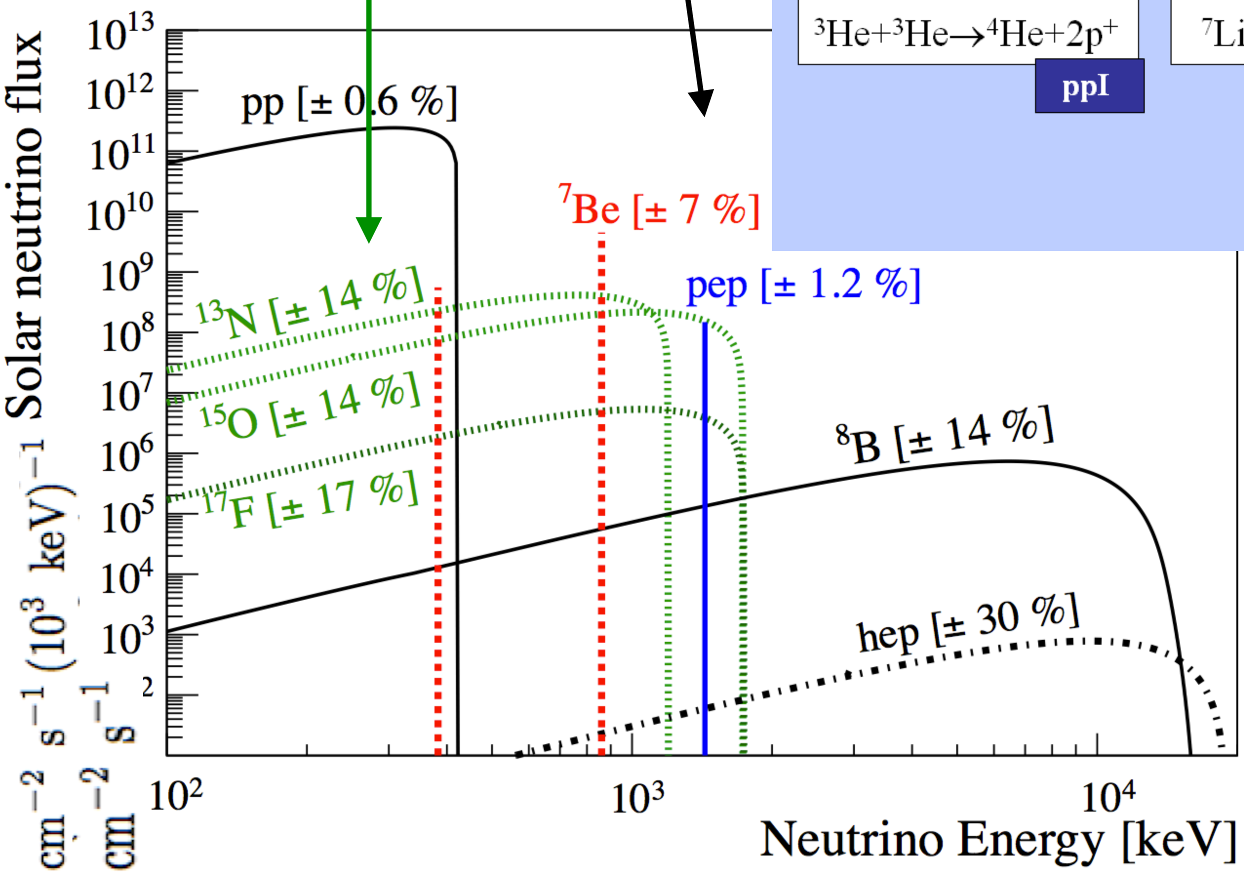
solar neutrinos

Standard Solar Model

J. N. Bahcall et al.

- solar **pp** chain:
  reactions, spectra
- solar **CNO** cycle
  spectra



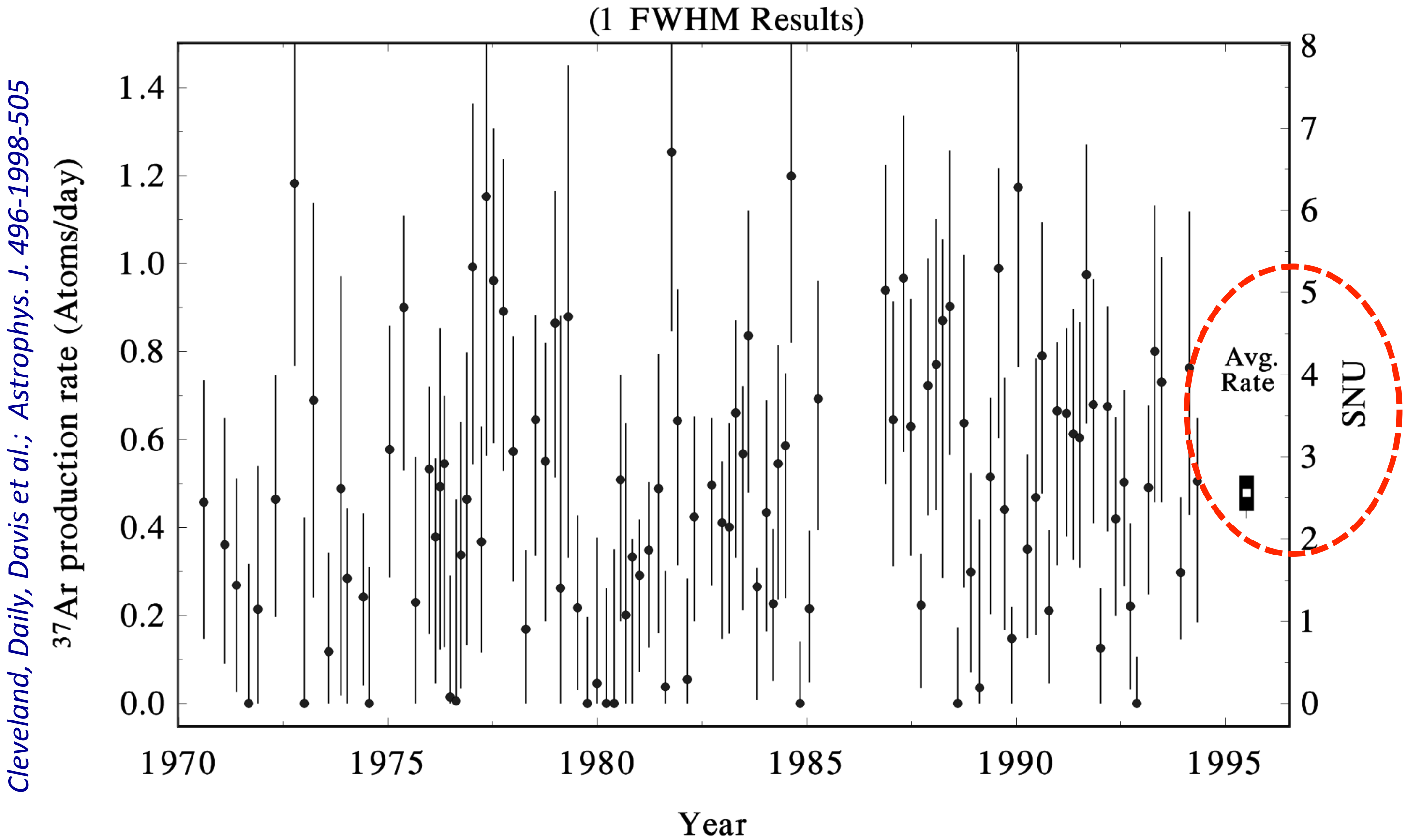


Bahcall, Serenelli, Basu; Astrophys. J. 621 (2005) 85
Serenelli, Haxton, Peña-Garay; Astrophys. J. 743 (2011) 24

Discovery of solar neutrinos; First hints of oscillating neutrinos [of missing e^- neutrinos]

R. Davis, Jr. Homestake Chlorine Detector

J. N. Bahcall $\nu + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ *1968 → …*



Final R. Davis J. et al.: 2.6 ± 0.2 (stat.) ± 0.2 (syst.) *SNU*

1 Solar Neutrino Unit = 1 interaction per 10^{36} target atoms s-1

Nobel 2002

Standard Solar Model: 9.3 ± 1.3 *SNU*

Bahcall, Pinsonneault, M. H. 1995, Rev. Mod. Phys., 67, 781

Nueva generación experimentos: (2)H_2O-Cherenkov

origen: búsqueda de la **desintegración del protón**

- en el Modelo Estándar, el protón es absolutamente estable
- sin embargo, dados
  - la estructura físico-matemática del MS,
  - las aproximaciones teóricas realistas para su evolución,
  - el conocimiento actual sobre la creación y desarrollo del Universo…

⇨ existe el "convencimiento" (intuición) de la no estabilidad del protón

es uno de los conceptos científicos más importante de la Humanidad

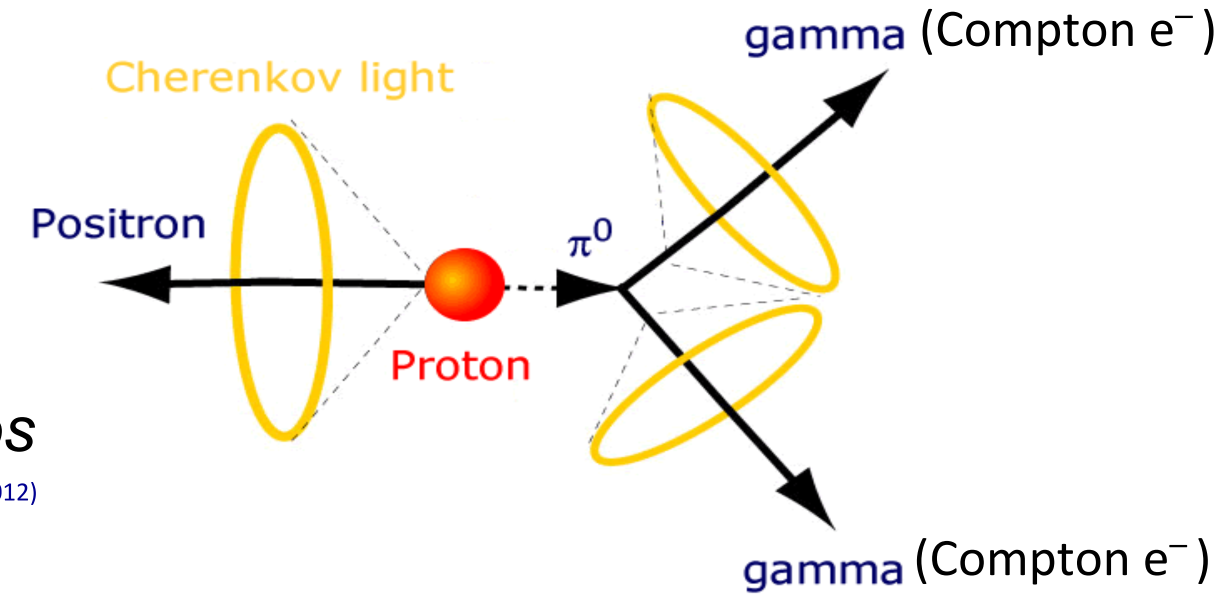
técnica Agua-Cherenkov permite instrumentar enormes cantidades de materia a observar

p.e.: $p \rightarrow e^+\pi^0$

no candidato hasta ahora

⇨ $\tau_p > 8.2 \times 10^{33}$ *años*

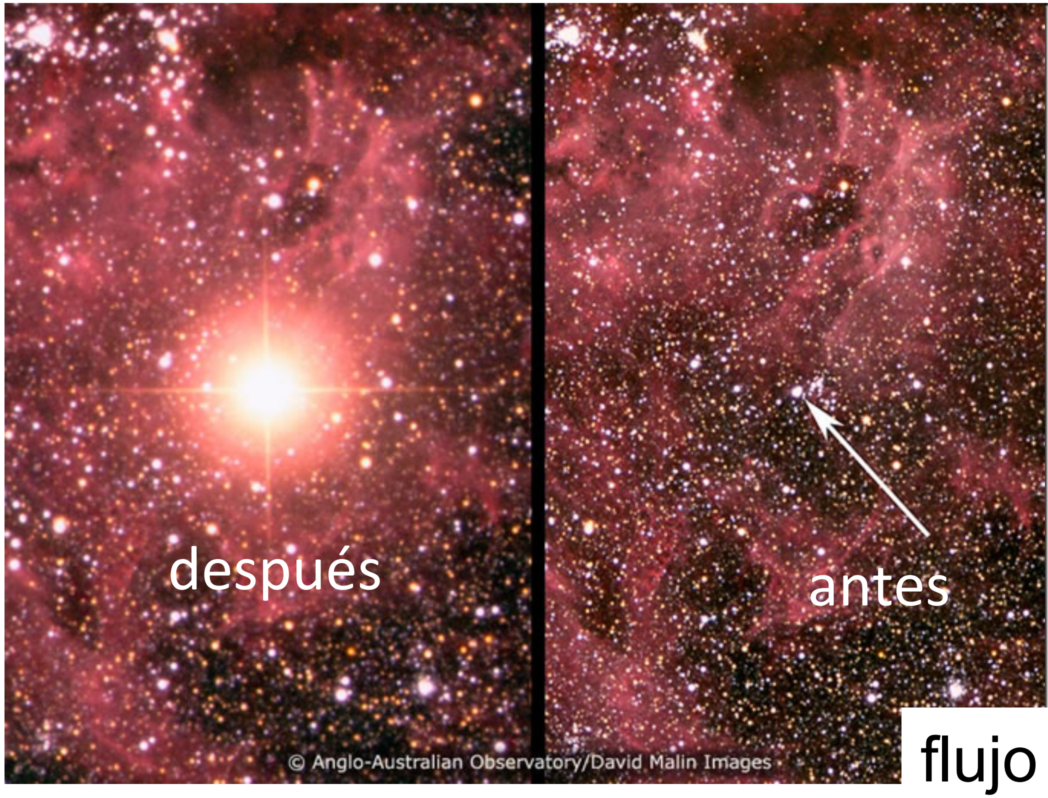
Super-Kamiokande, Phys. Rev. D 85, 112001 (2012)

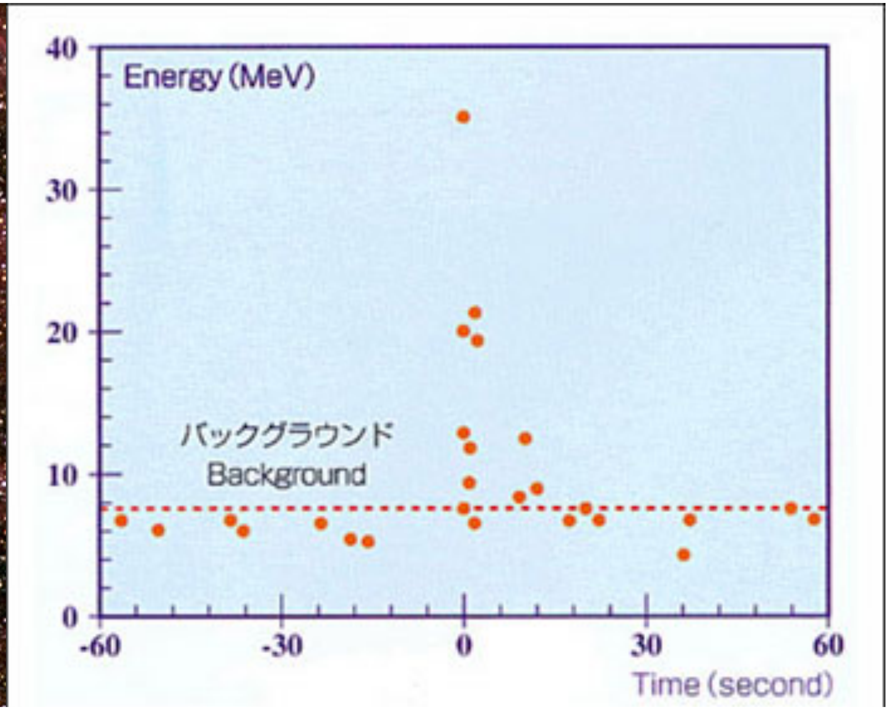


pero la propia Naturaleza nos hizo descubrir que este tipo de detectores son extraordinarios *telescopios de neutrinos*

Kamiokande; Phys. Rev. Lett. 58 (1987) 1490
IMB; Phys. Rev. Lett. 58 (1987) 1494

SuperNova SN1987A (Gran Nube de Magallanes)





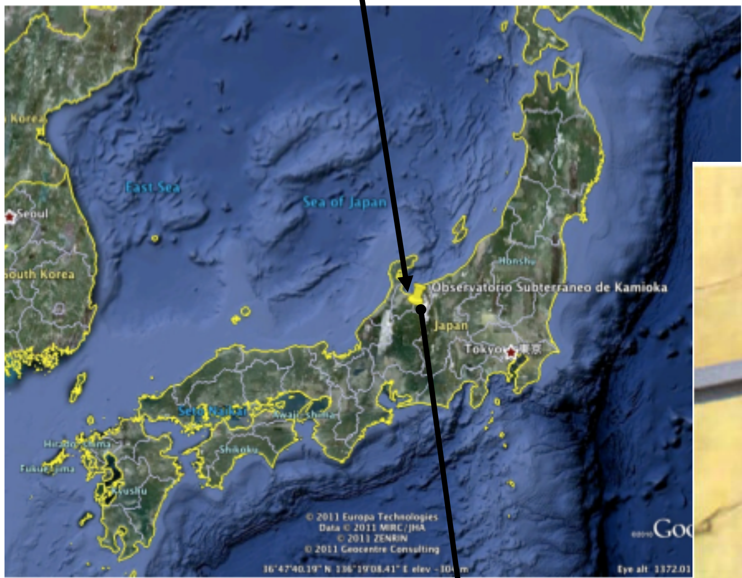
flujo y espectro de ν's medido por Kamiokande (precursor de SK)

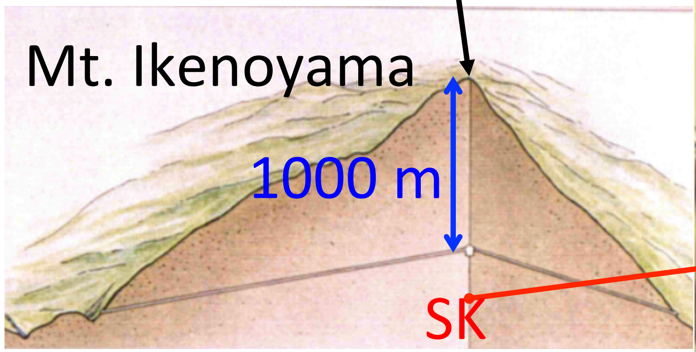
telescopios con los que, además de éste (Nobel 2002), se han hecho otros descubrimientos fundamentales (Nobel 2015, …)

Super-Kamiokande (SK) paradigma de detector agua-Cherenkov

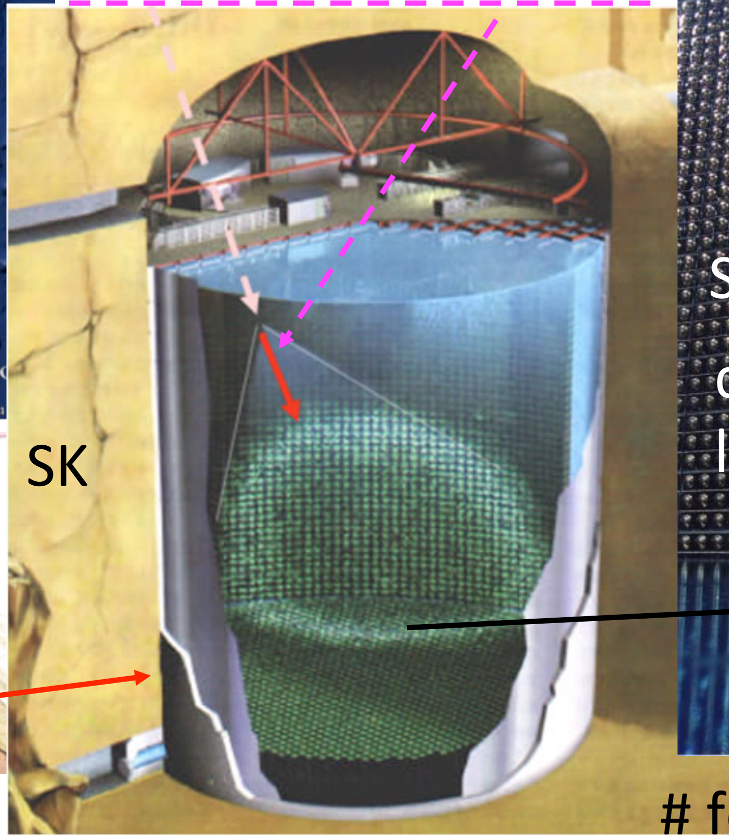
Observatorio de Kamioka (Prefectura Gifu, Japón)

SK mide la radiación Cherenkov generada por las partículas con carga y alta energía

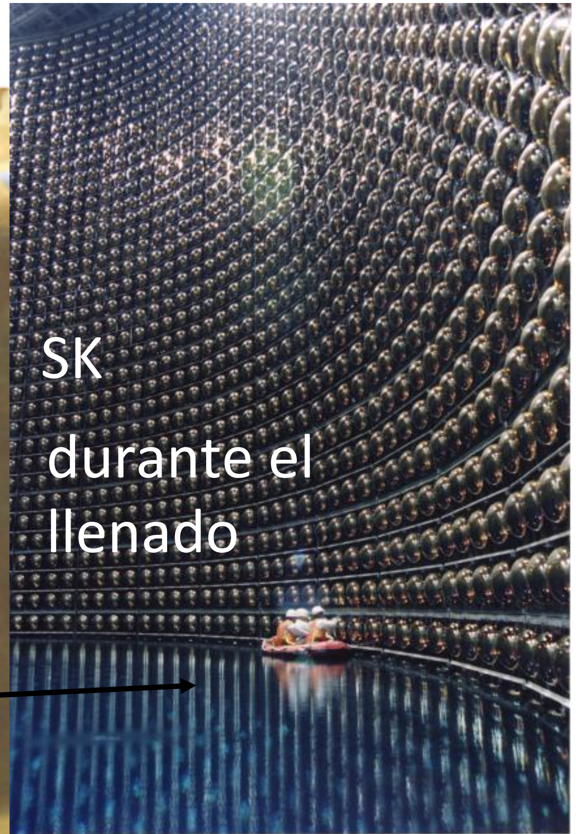




1000 m de tierra para apantallar muones de rayos cósmicos



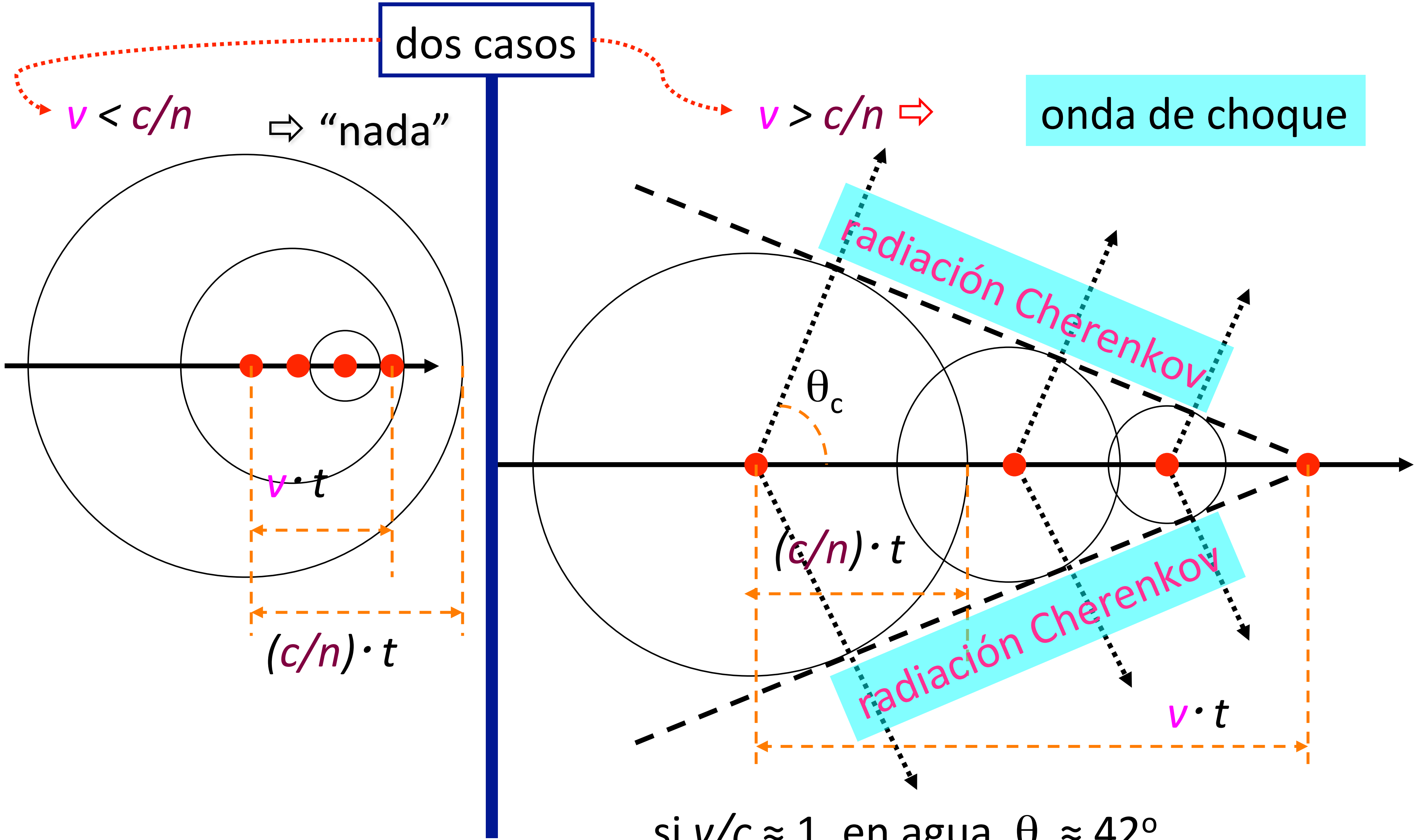
50.000 m^3 de agua
tanque: 40m ∅ x 40m H



fotomultiplicadores
11148 de 50 cm ∅
1885 de 20 cm ∅

Básico de la radiación Cherenkov

una partícula cargada moviéndose en un medio con velocidad v genera un campo EM que se propaga con velocidad c/n

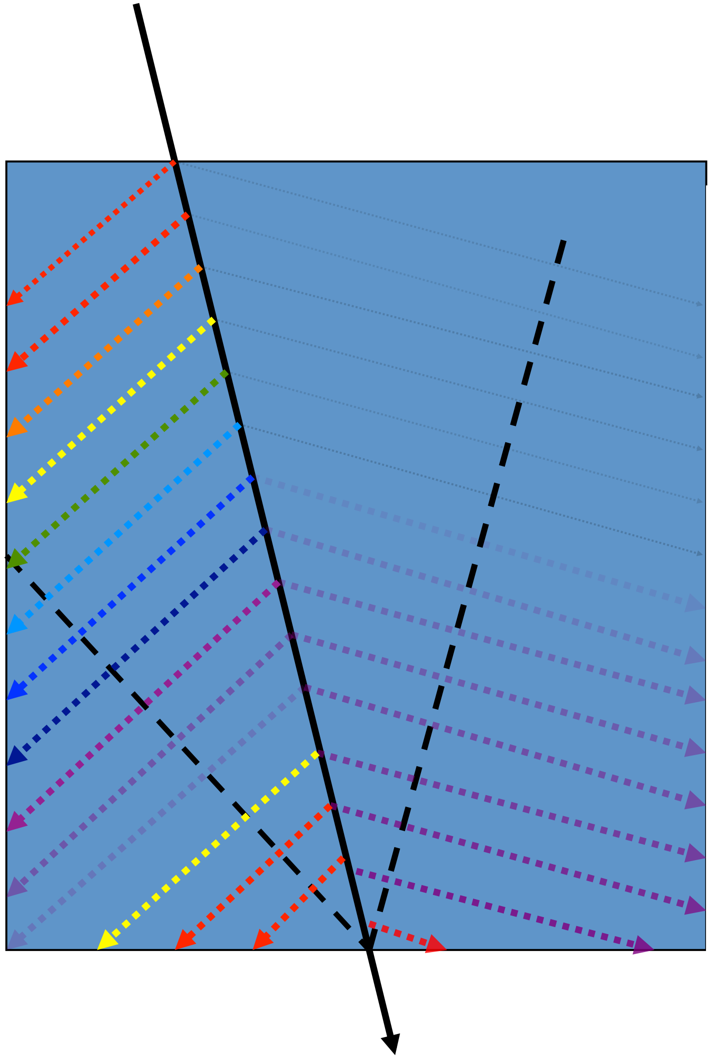


si $v/c \approx 1$, en agua, $\theta_c \approx 42^o$

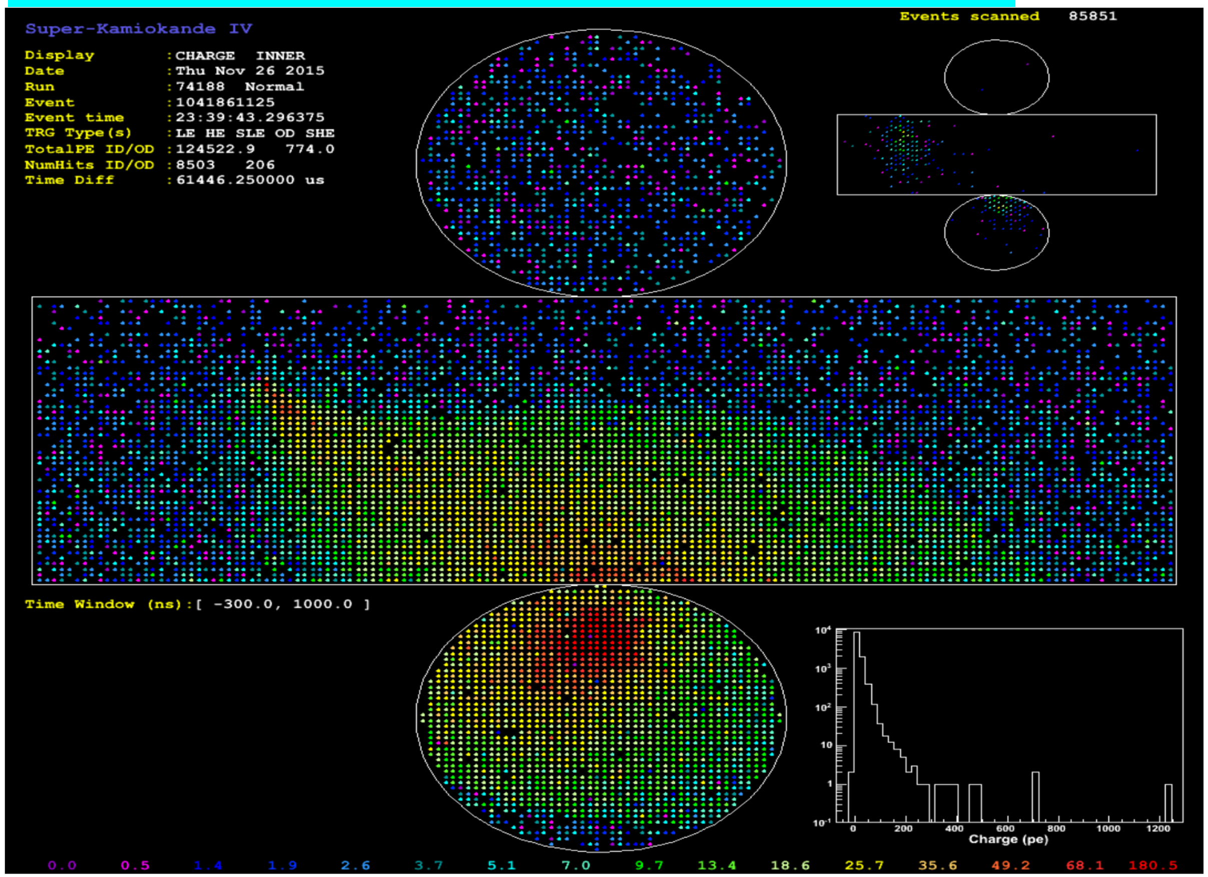
p.e.: la medida del tiempo que tarda la luz Cherenkov en llegar a los PMT's

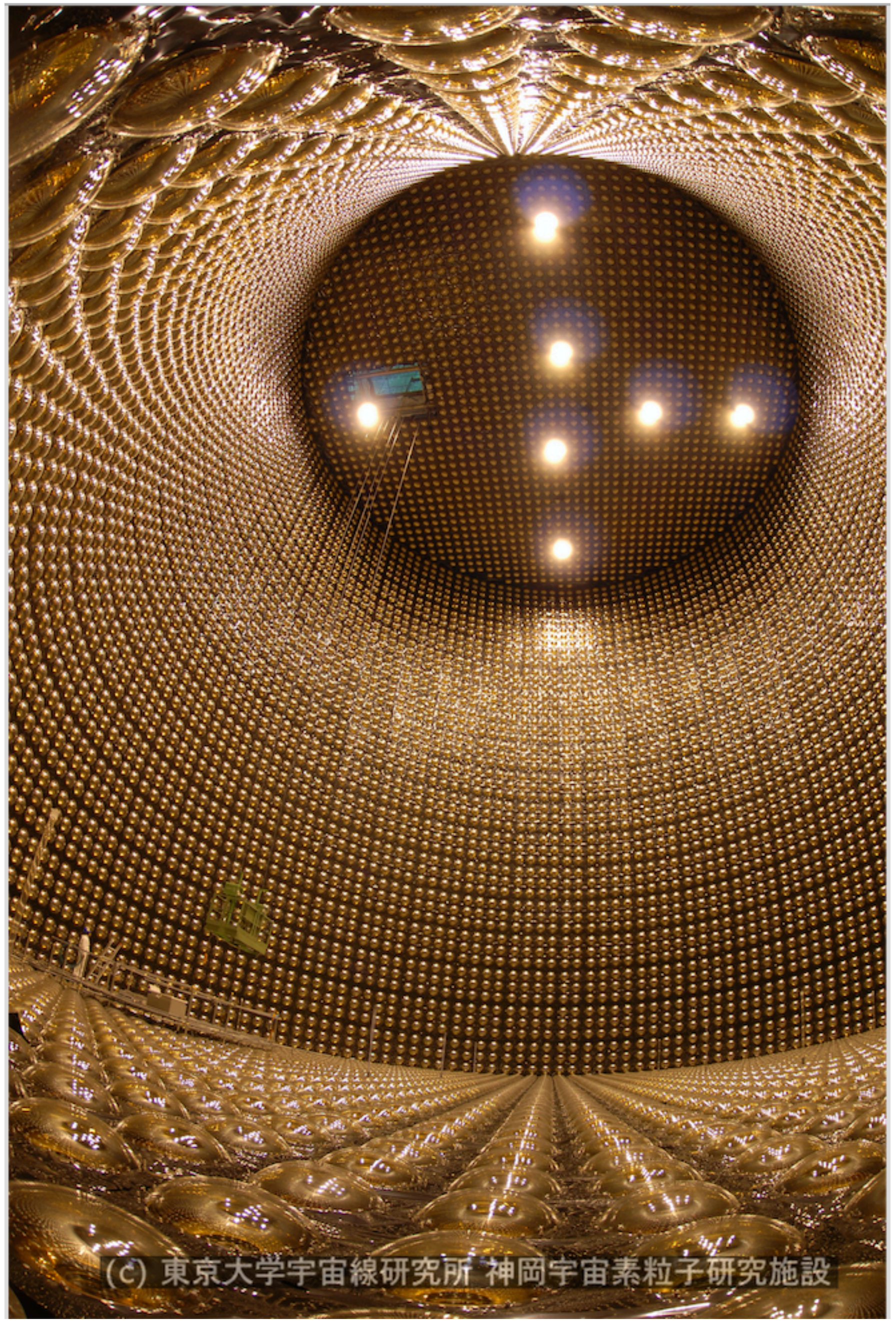
rojo: corto
púrpura: largo
púrpura suave: muy largo

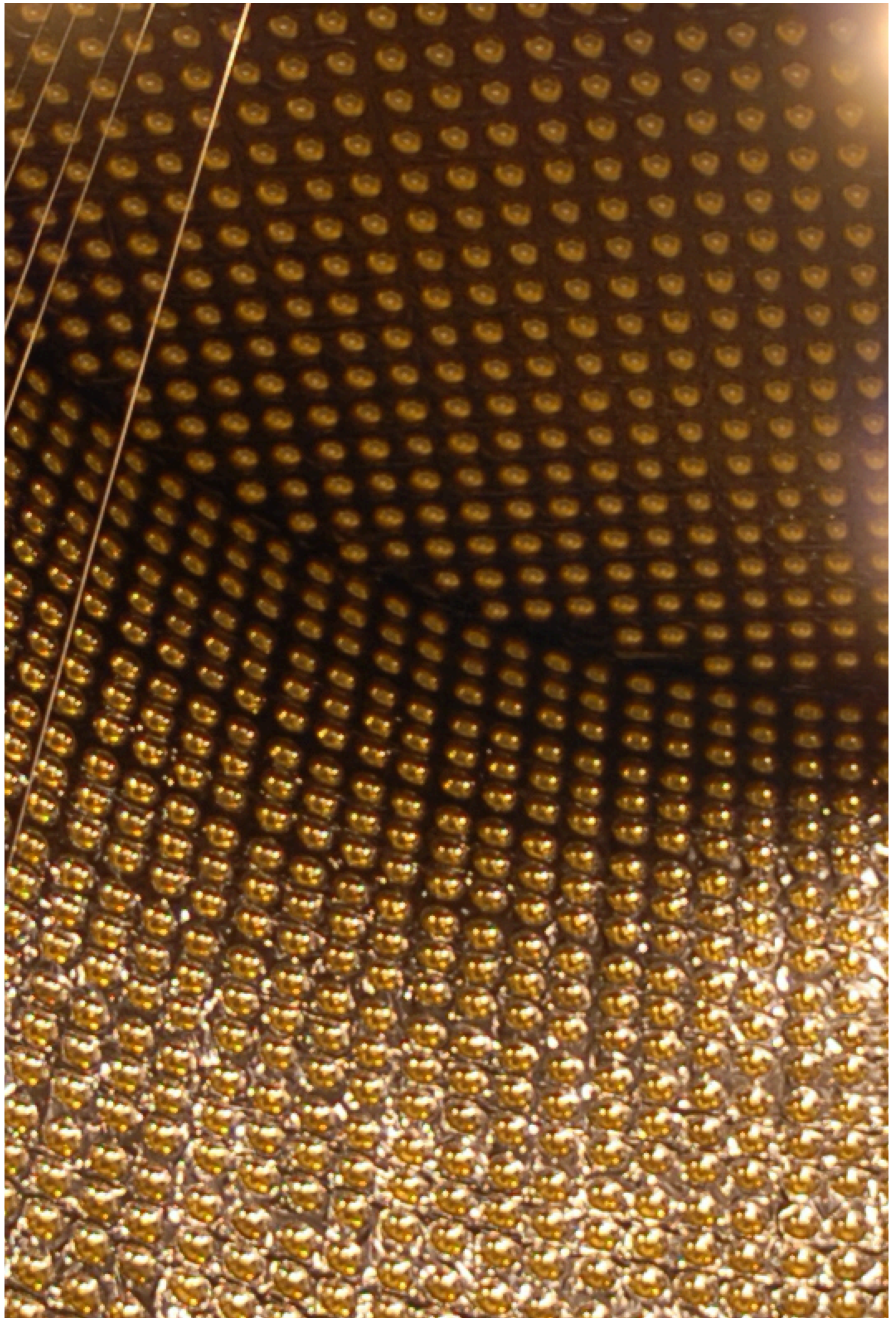
nos permite reconstruir la trayectoria de las partículas …



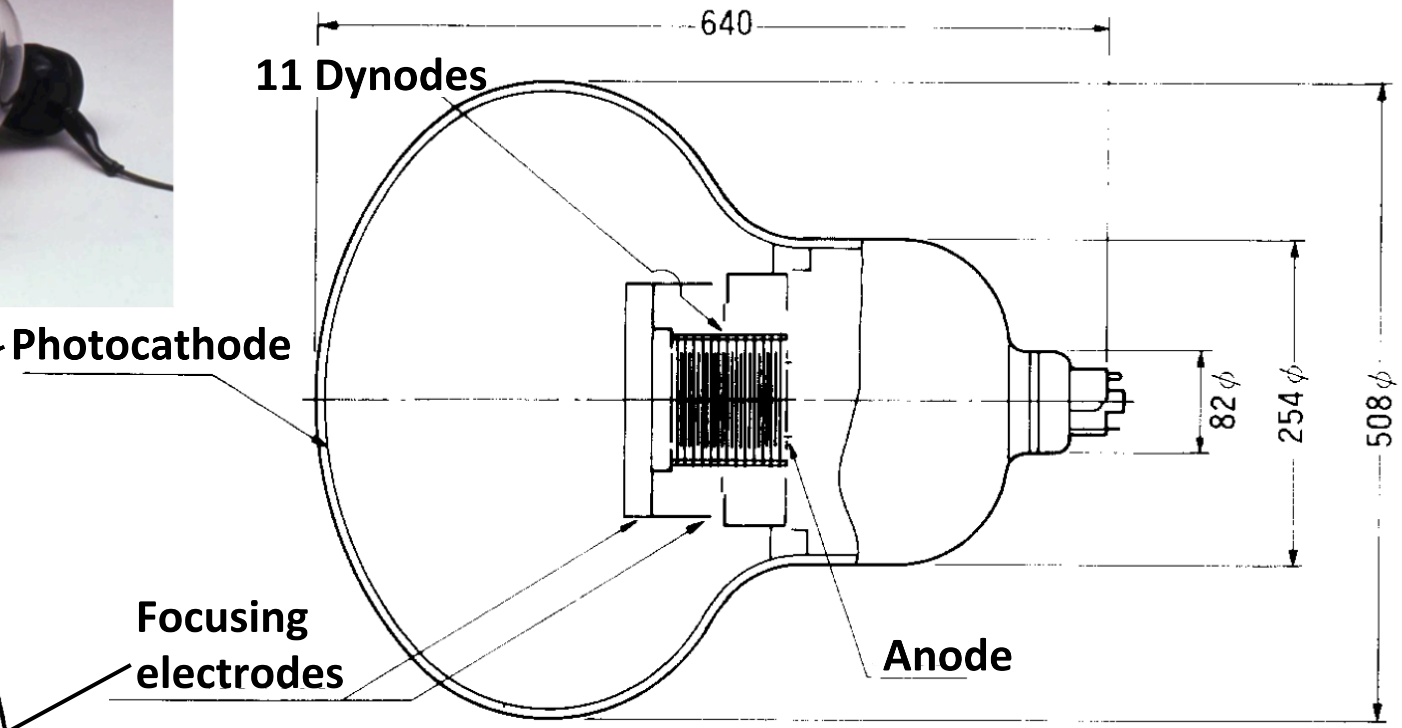
1 muón incidiendo por arriba izquierda
medida de carga

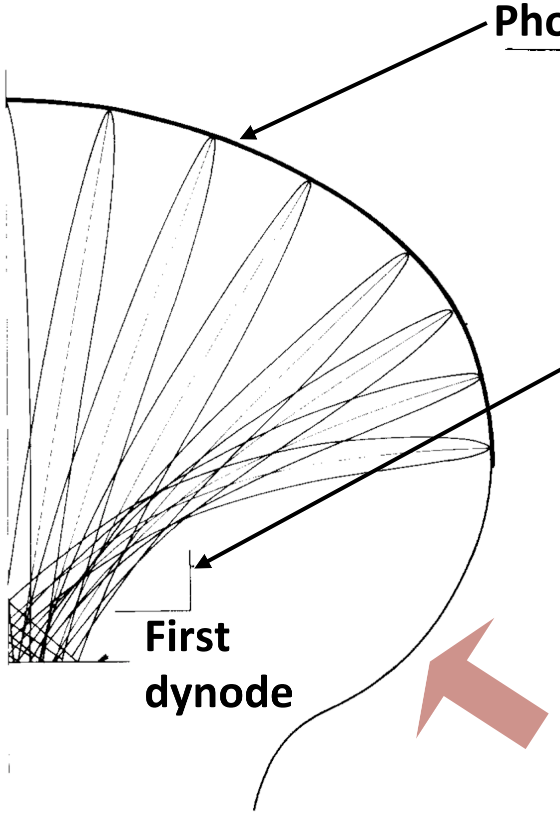



(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設



Basic sketch:





operating gain / voltage:

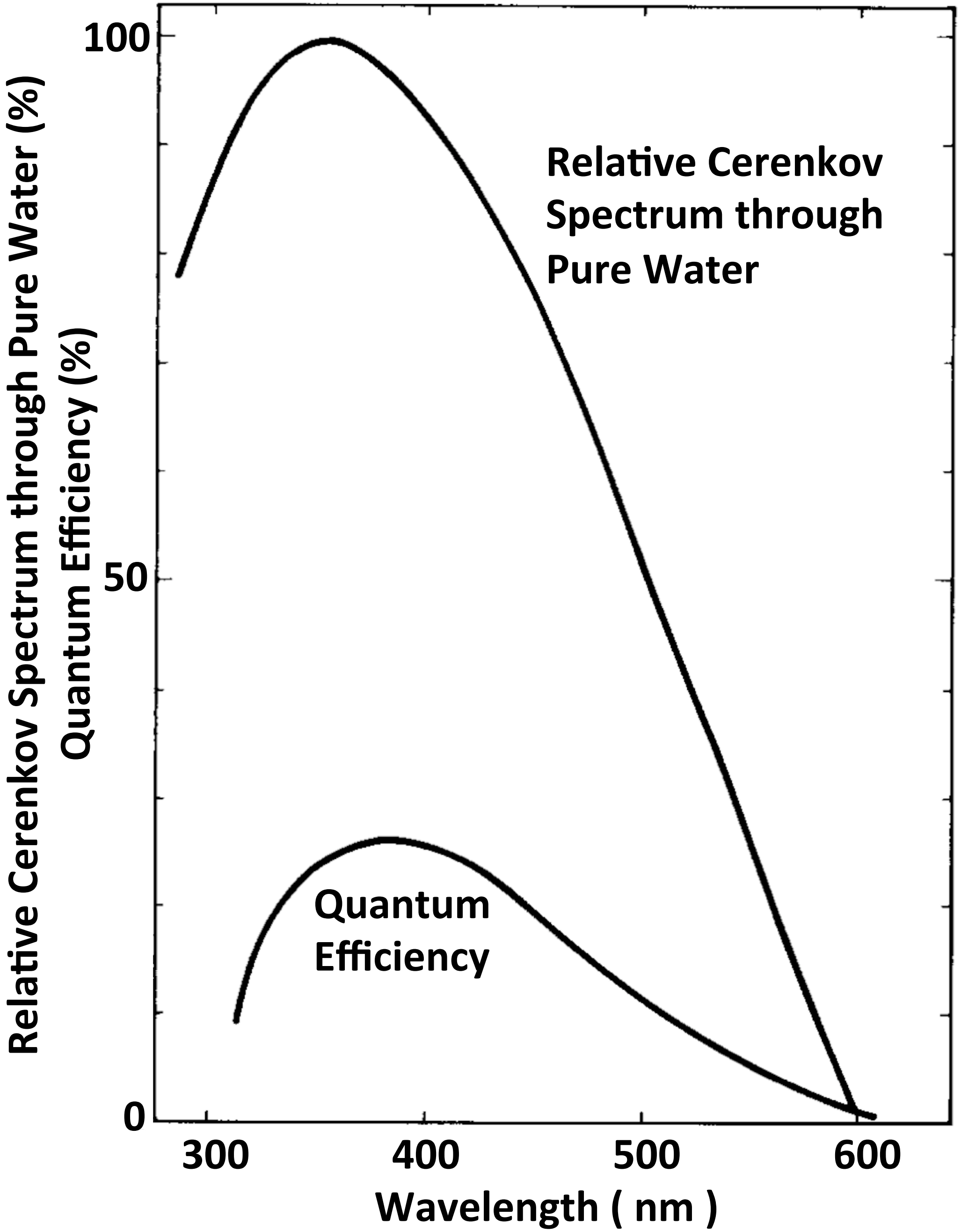
10^7 / 1700 – 2000 V

computer simulation of
electron trajectories

timing resolution ≈2 ns

1 p.e. charge resolution: 53 %

dark noise (< 0.25 p.e.) ≈3 kHz



ν_μ interaction

probably CC:

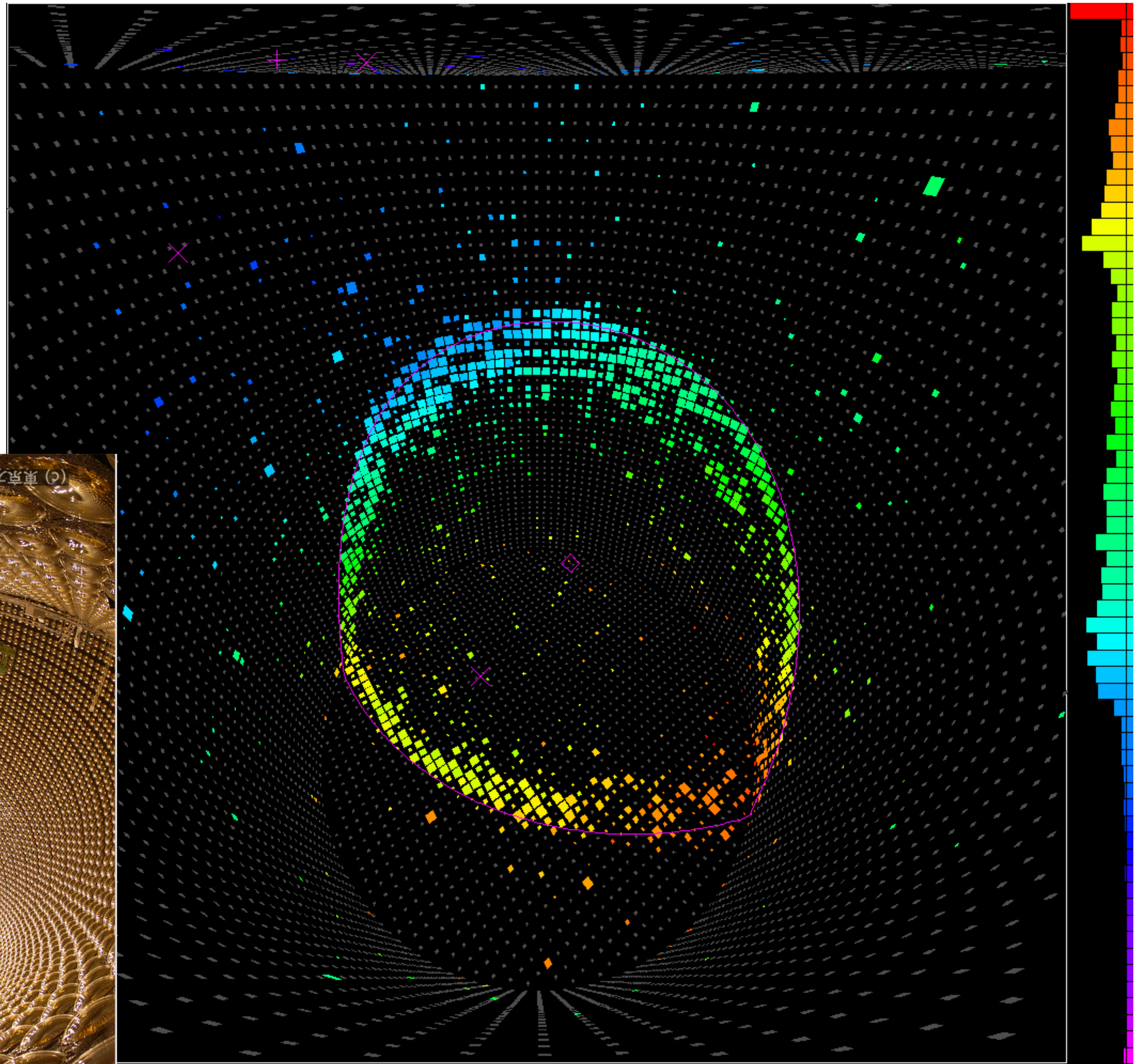
$\nu_\mu \, n \longrightarrow \mu^- \, p$

Seen is the μ^- reconstructed

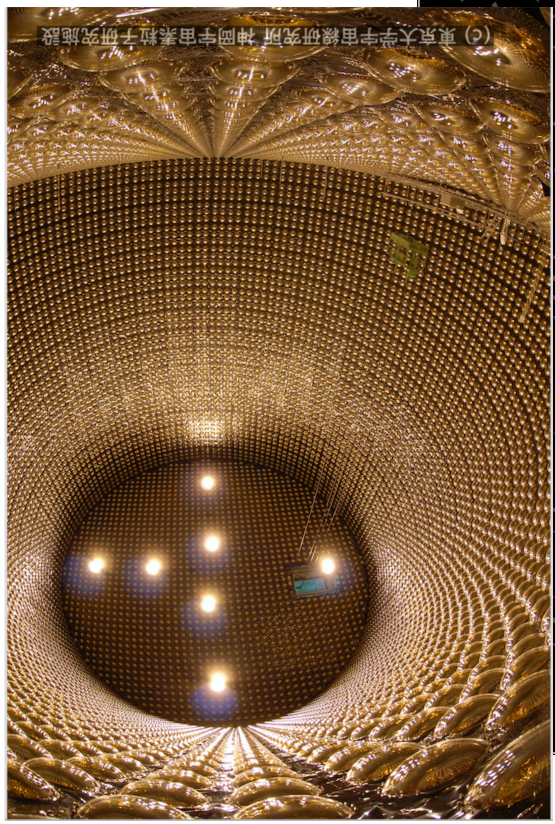
E[μ]= 603 MeV

color scale: time

late time



early time



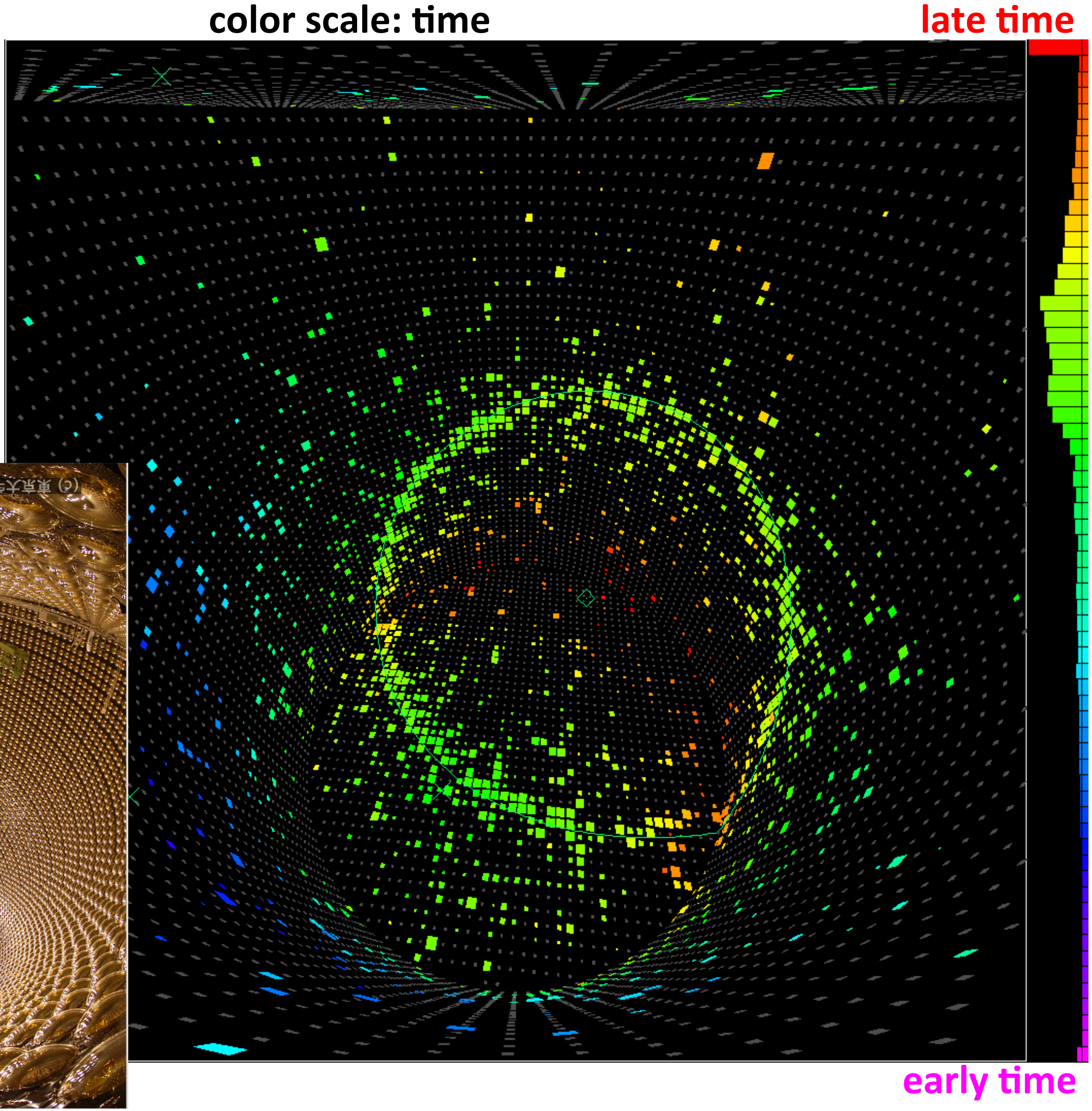
ν_e interaction

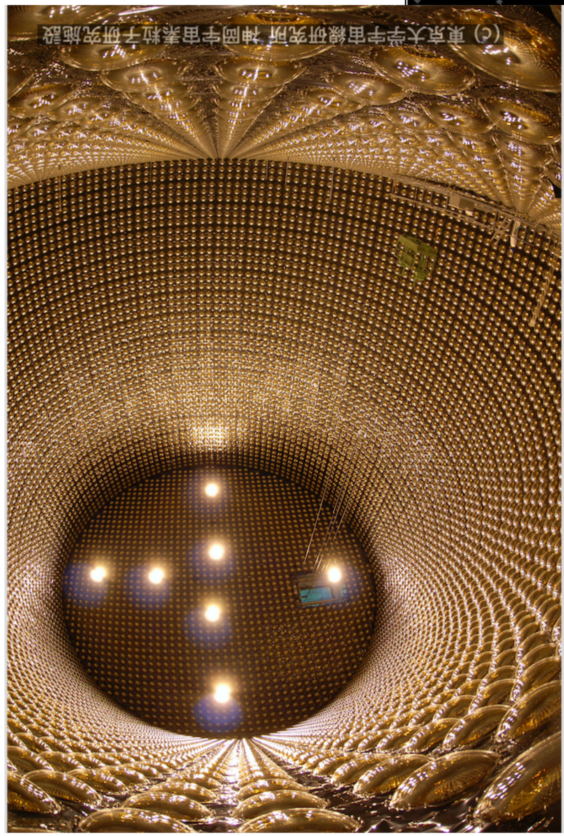
probably CC:

$\nu_e\, n \longrightarrow e^-\, p$

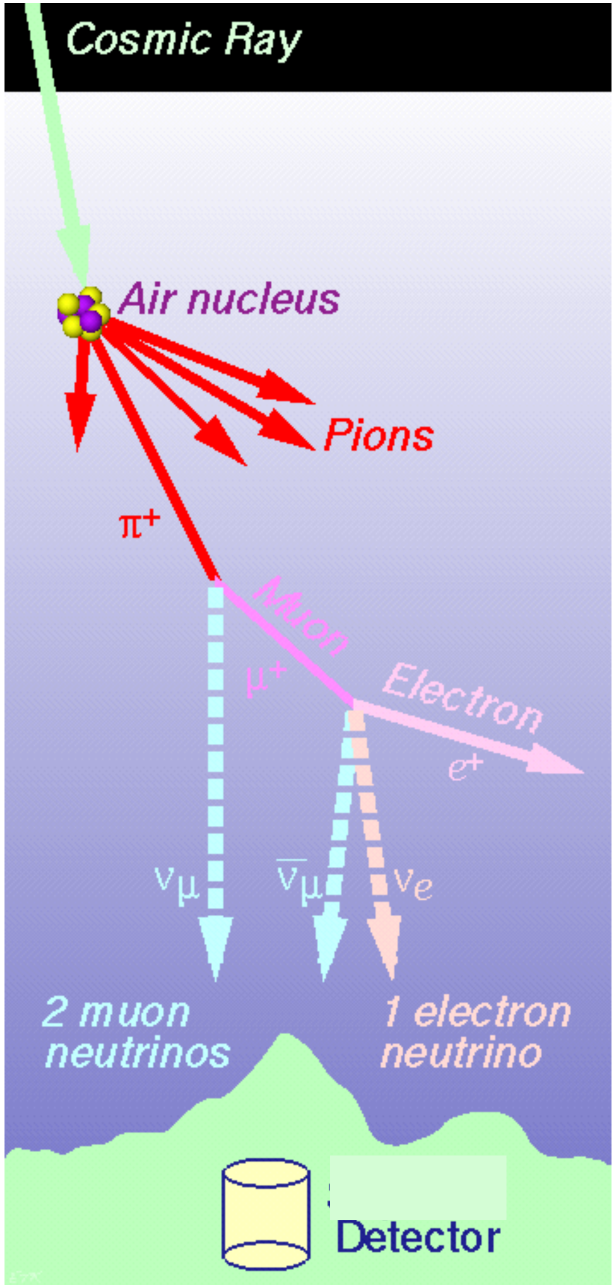
Seen is the e^- reconstructed

$E[e^-] = 492$ MeV





Atmospheric ν's



result from the decay of particles produced in the interactions of Cosmic Rays with the atmosphere (mainly $K^{\pm}$, $\pi^{\pm}$, $\mu^{\pm}$)

K^+ DECAY MODES http://pdg.lbl.org (June 2010)

		Fraction (Γ_i/Γ)
Leptonic and semileptonic modes		
$K^+ \rightarrow e^+ \nu_e$		$(1.55 \pm 0.07) \times 10^{-5}$
$K^+ \rightarrow \mu^+ \nu_\mu$		(63.55 ± 0.11) %
$K^+ \rightarrow \pi^0 e^+ \nu_e$ Called K^+_{e3}.		(5.07 ± 0.04) %
$K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$ Called $K^+_{\mu 3}$.		(3.353 ± 0.034) %

π^+ DECAY MODES

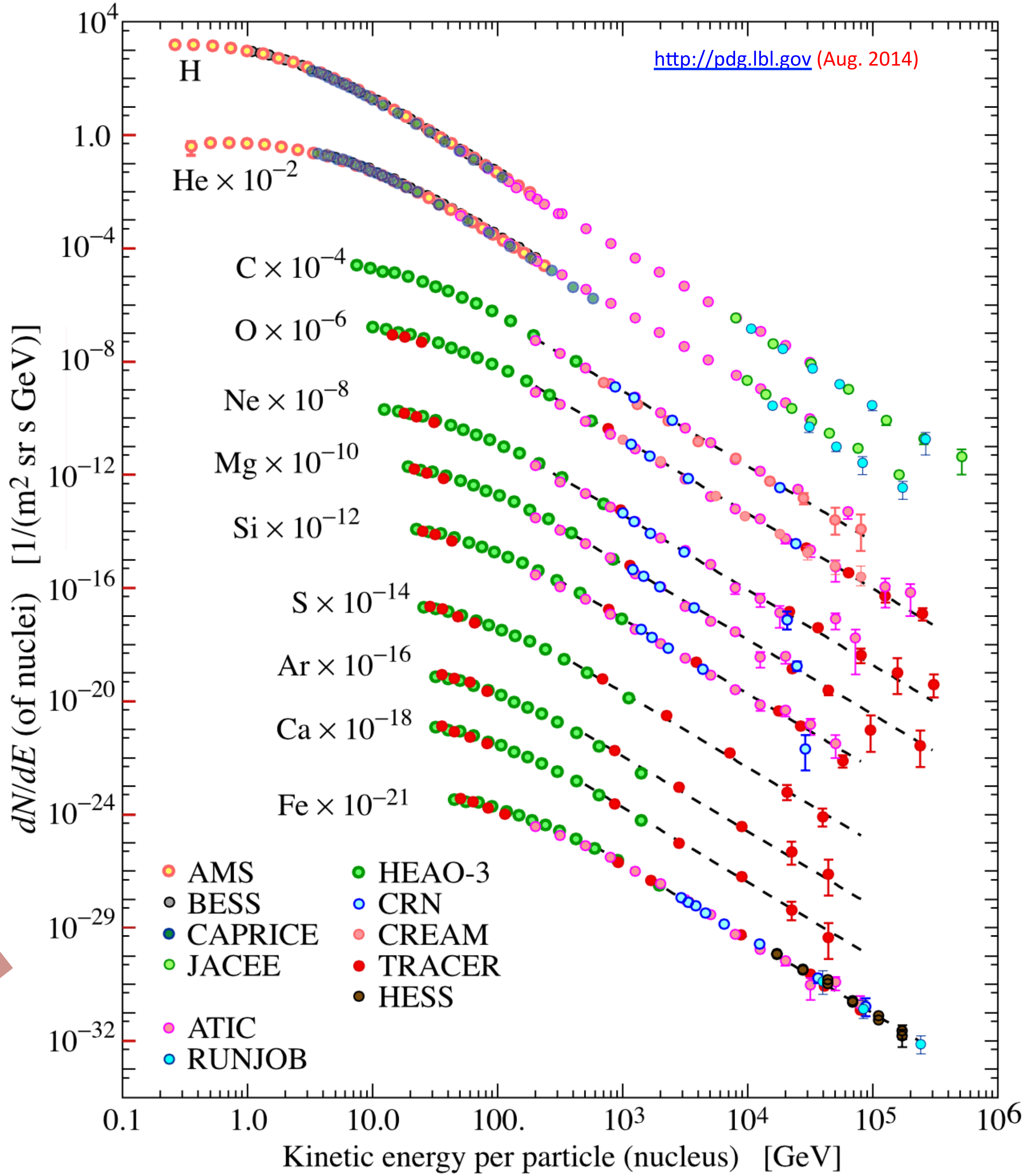
		Fraction (Γ_i/Γ)
$\mu^+ \nu_\mu$	[b]	(99.98770 ± 0.00004) %
$\mu^+ \nu_\mu \gamma$	[c]	$(2.00 \pm 0.25) \times 10^{-4}$
$e^+ \nu_e$	[b]	$(1.230 \pm 0.004) \times 10^{-4}$

μ^- DECAY MODES

		Fraction (Γ_i/Γ)
$e^- \overline{\nu}_e \nu_\mu$		$\approx 100\%$
$e^- \overline{\nu}_e \nu_\mu \gamma$	[d]	(1.4 ± 0.4) %
$e^- \overline{\nu}_e \nu_\mu e^+ e^-$	[e]	$(3.4 \pm 0.4) \times 10^{-5}$

they span a very large range of energy

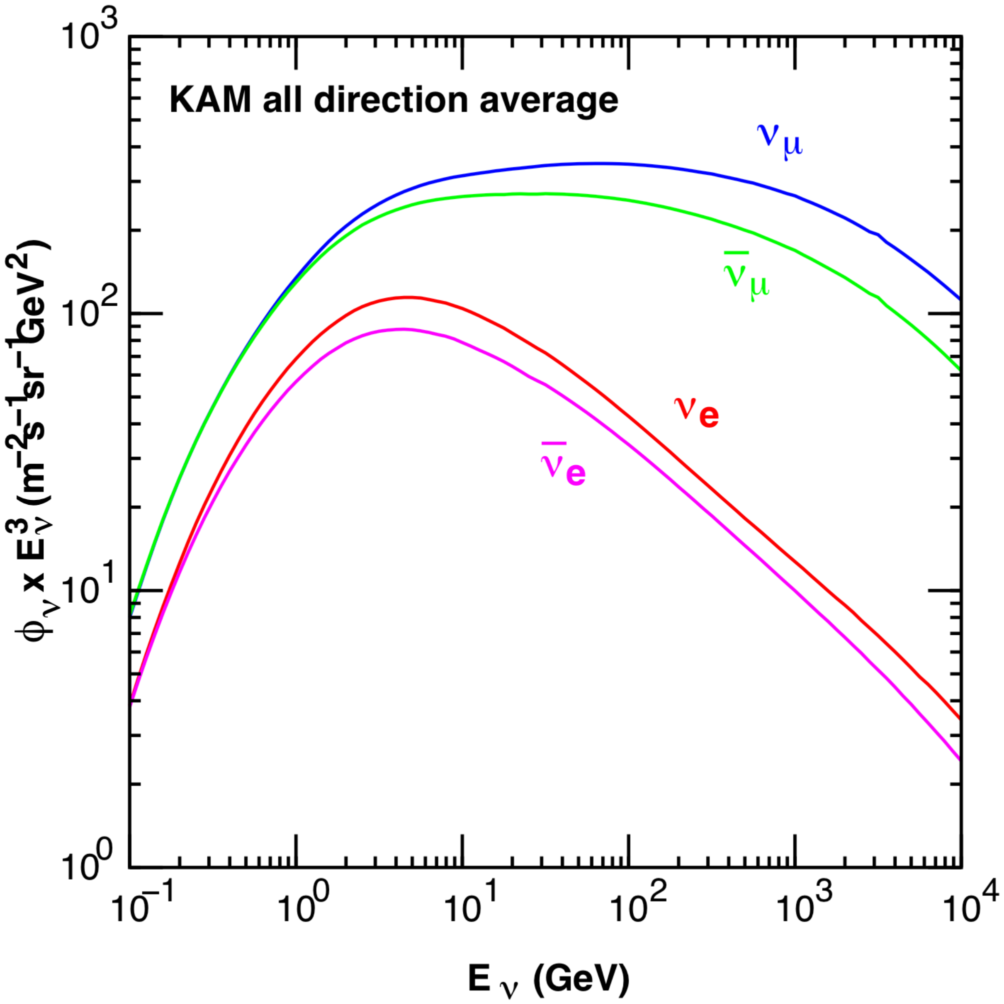
Major components of primary CR radiation:

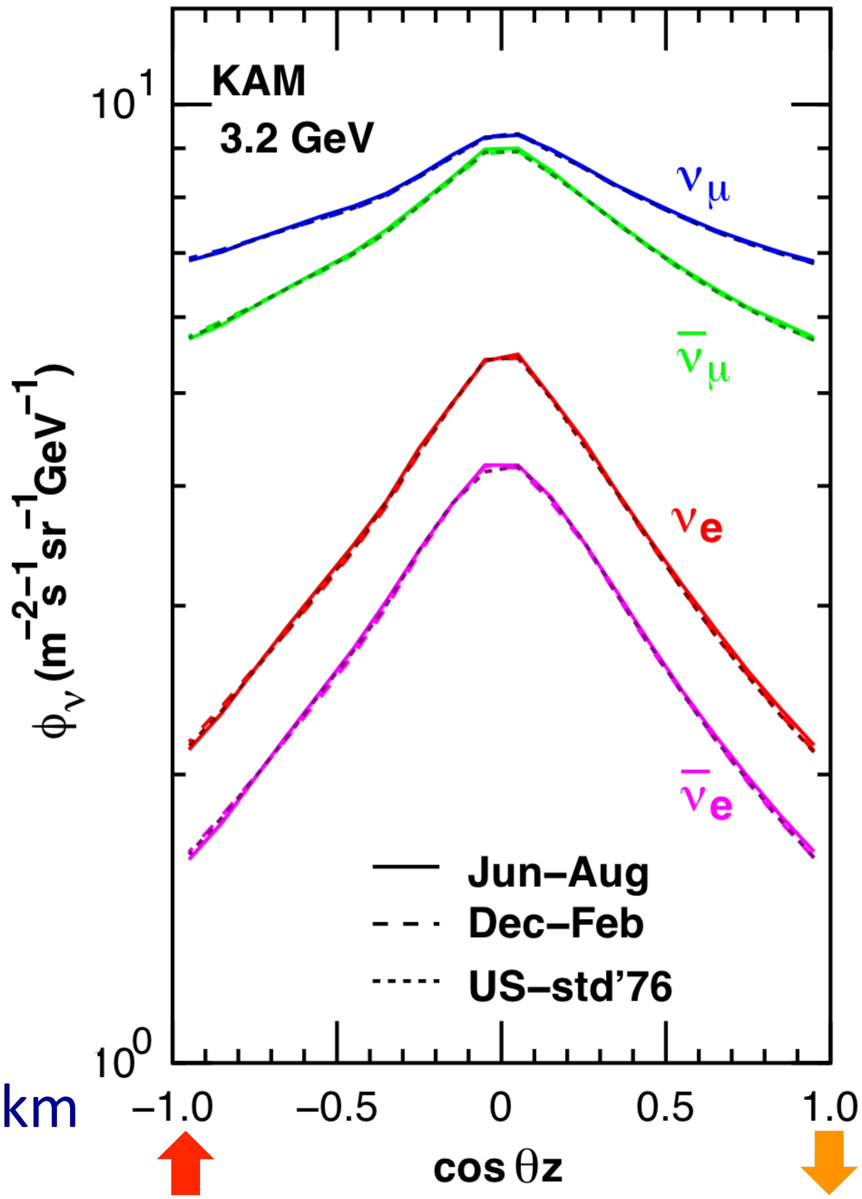


Estimate ν flux:

Atmospheric Neutrinos: Predicted Fluxes at Super-Kamiokande

M. Honda, M.S. Athar, **T. Kajita**, K. Kasahara, S. Mirdorikawa; arXiv:1502.03916v2





upwards, travel ≈13000 km

downwards, travel ≈ 15 km

Main interactions

Elastic $\nu + e \rightarrow \nu + e$

quasi-elastic

CC:

$\nu_l n \rightarrow l^- p$

$\bar{\nu}_l p \rightarrow l^+ n$ (IBD) ← **< 1 GeV**

1 meson *CC:*

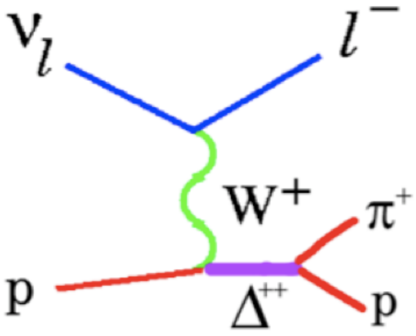
a) $\nu N \rightarrow l N^*, N^* \rightarrow m N'$

N, N′: nucleons

N: baryon resonance*

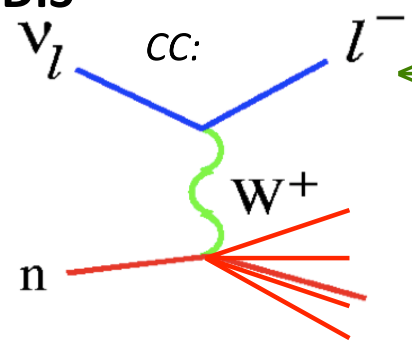
m: meson (π's, also K, η)

b) coherent π production: $\nu\, {}^{16}O \rightarrow l\, \pi\, {}^{16}O$



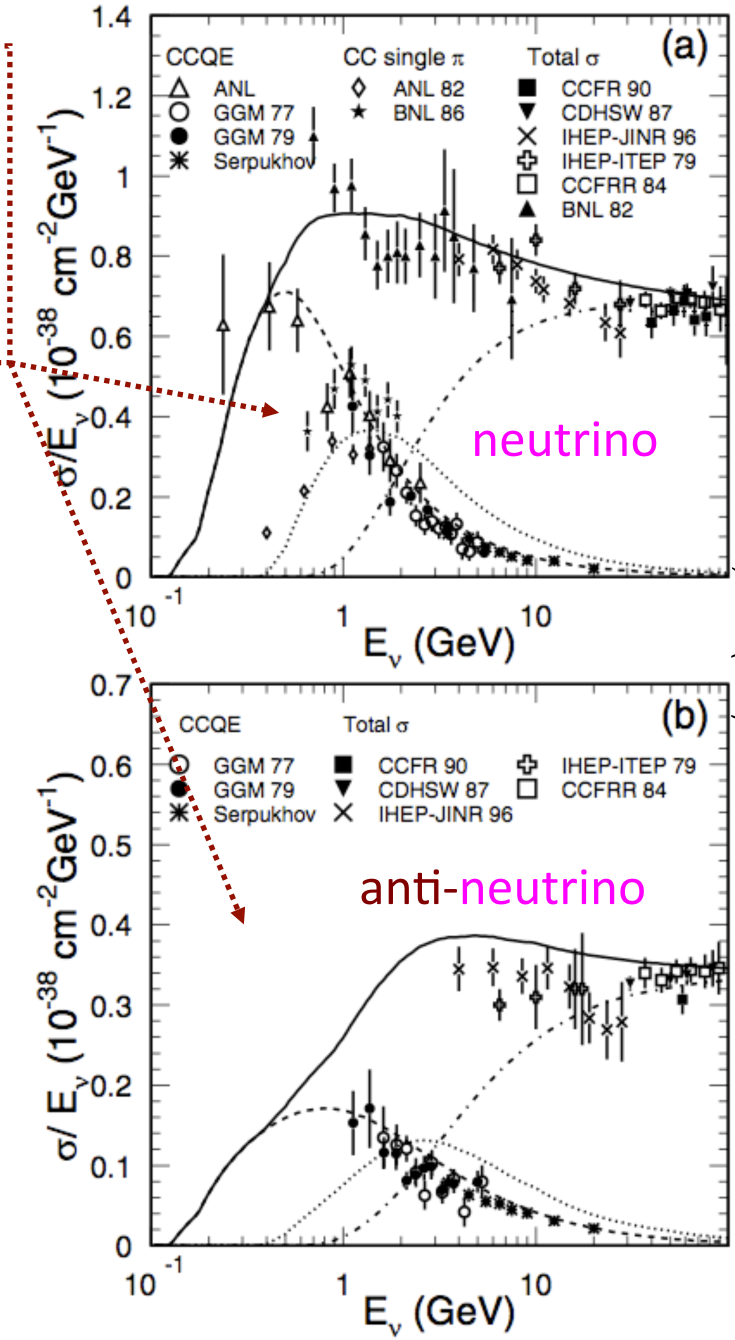
↑ **~ 1 GeV**

DIS



← **High Energy**

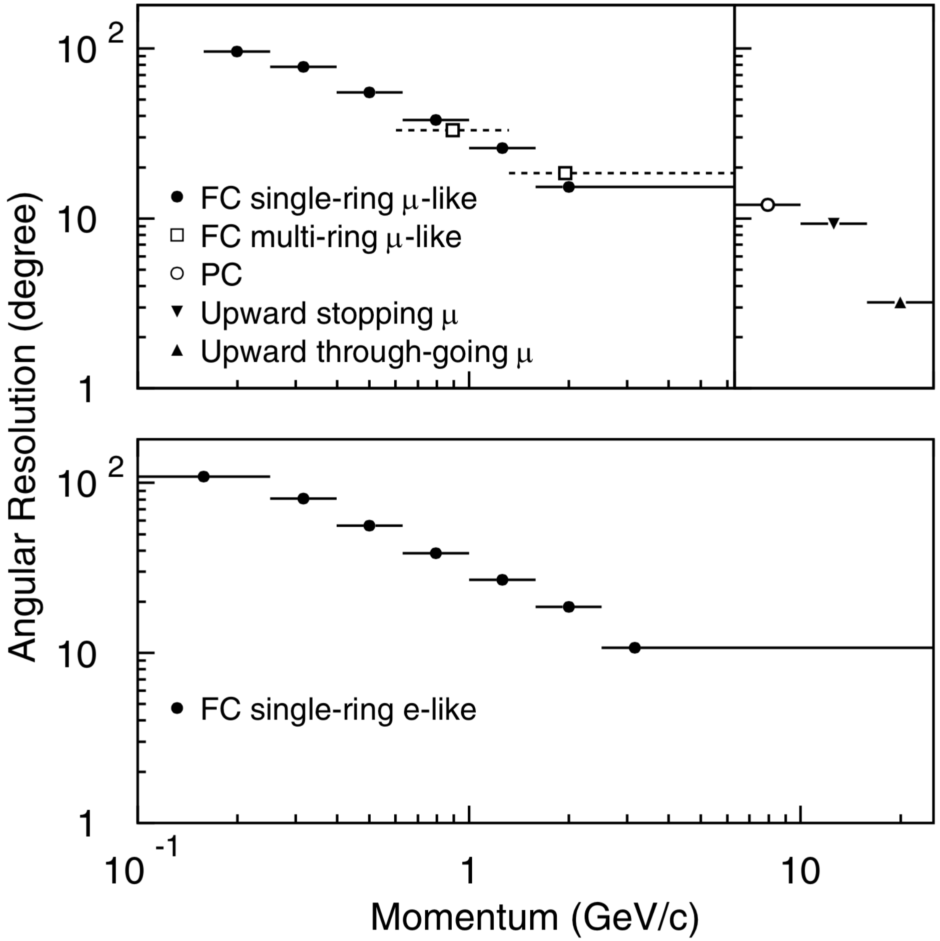
- - - - CCQE
········ CC single π
- · - · DIS
——— total



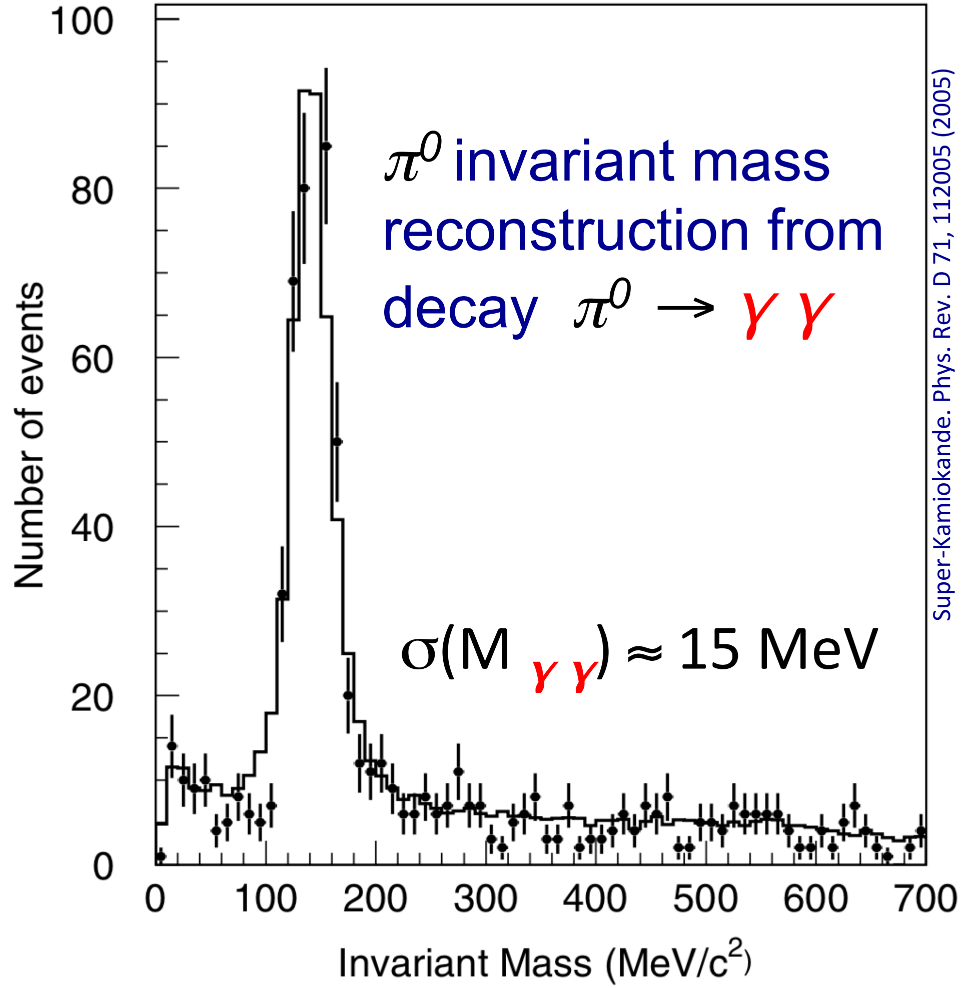
SK Collab.; PRD71(2005)112005

Atmospheric νs reconstruction by Super-Kamiokande

Angular resolution for different type of events vs. momentum



Momentum reconstruction

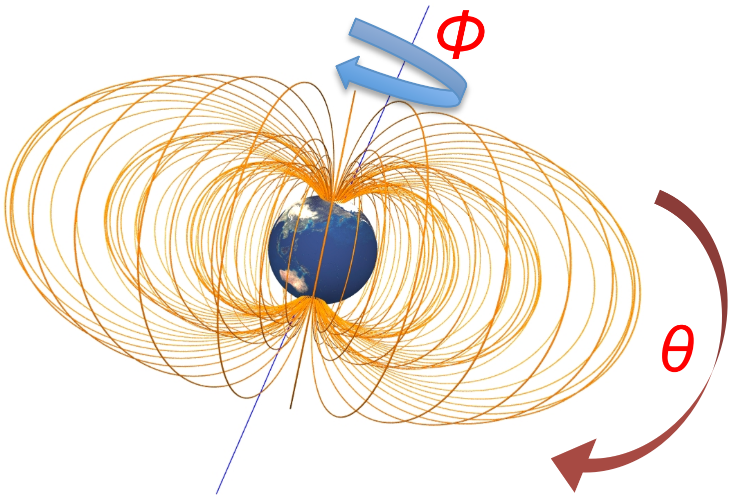


π^0 invariant mass reconstruction from decay $\pi^0 \rightarrow \gamma\,\gamma$

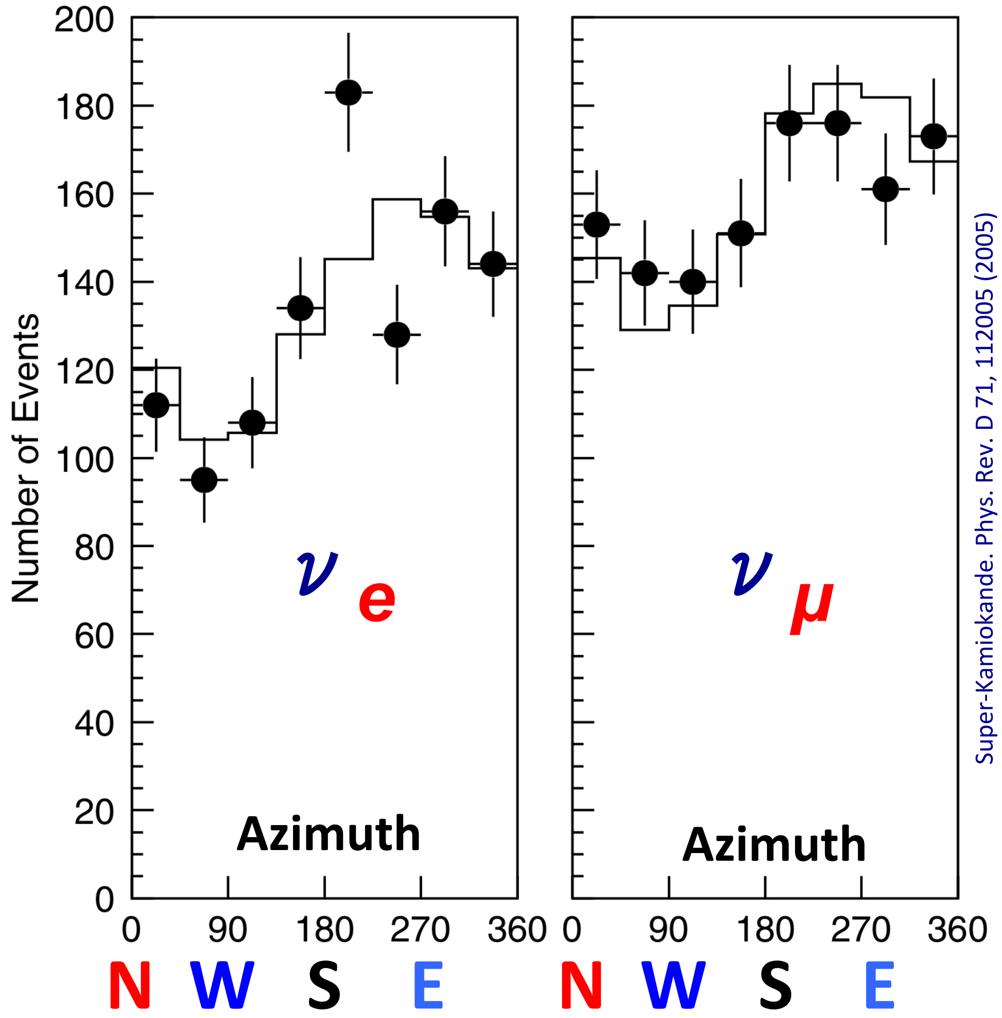
$\sigma(M_{\gamma\gamma}) \approx 15$ MeV

Super-Kamiokande. Phys. Rev. D 71, 112005 (2005)

ν_e, ν_μ fluxes vs. incidence angle: Φ symmetry must hold
[not really because of earth magnetic field: **E** – **W** effect]

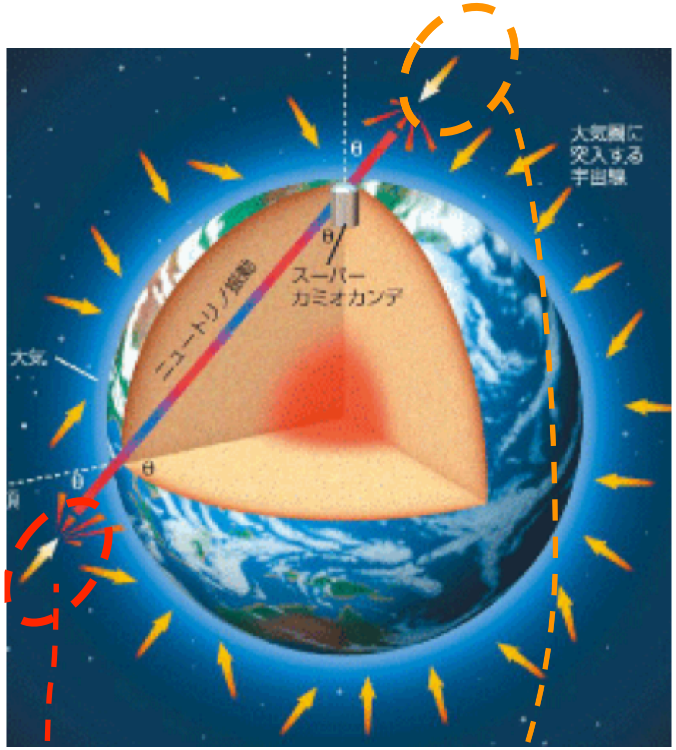


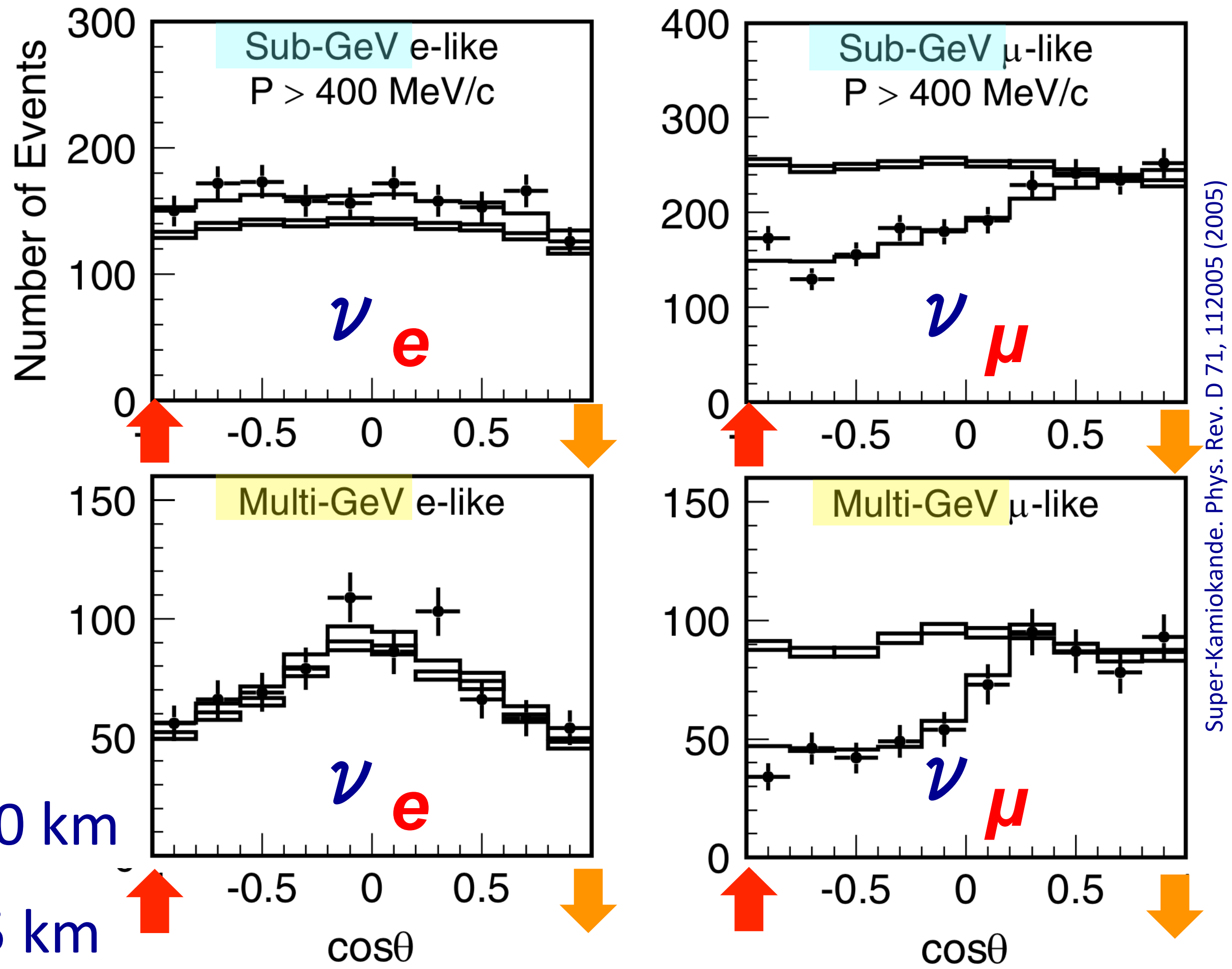
0.4 GeV < E(ν) < 3 GeV
| cos θ | < 0.5



→ Φ (azimuth) symmetry holds

ν_e, ν_μ fluxes vs. energy and θ incidence angle (zenith)





upwards, travel ≈13000 km

downwards, travel ≈ 15 km

measured ν_μ flux strongly dependent on travel distance

→ ν_μ oscillates → **massive ν_x** ✓

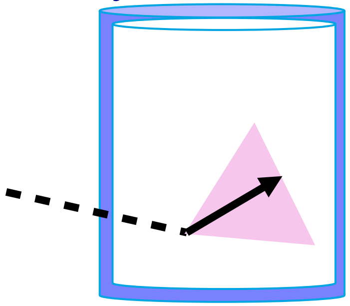
(mainly to ν_τ)

Nobel 2015

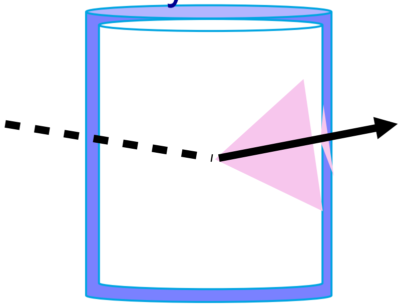
small effects on ν_e
(note high energy)

A full oscillation analysis:

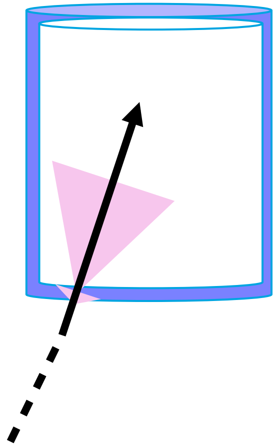
Fully **C**ontained

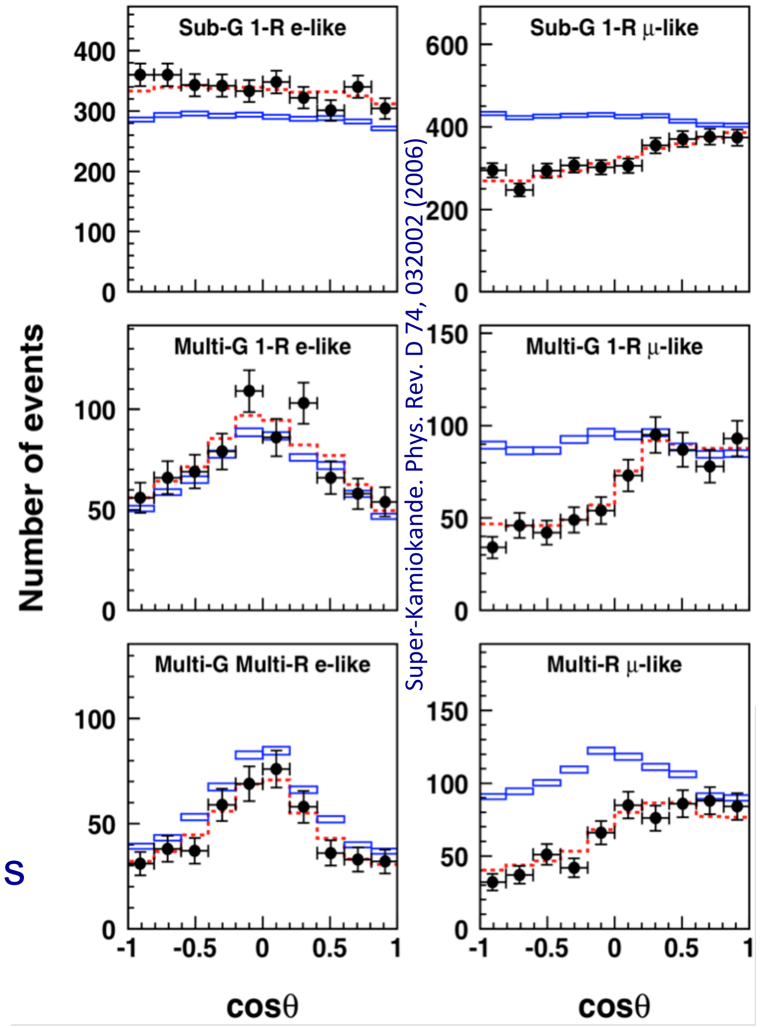


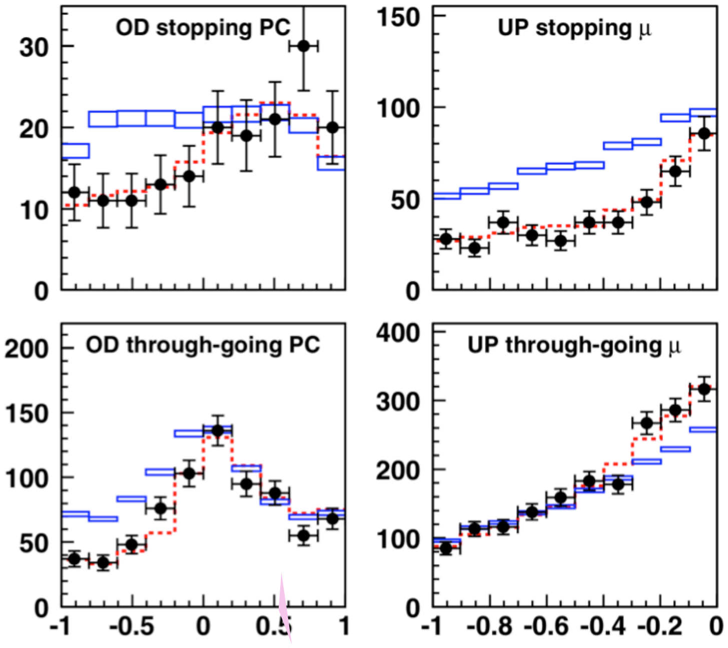
Partially **C**ontained

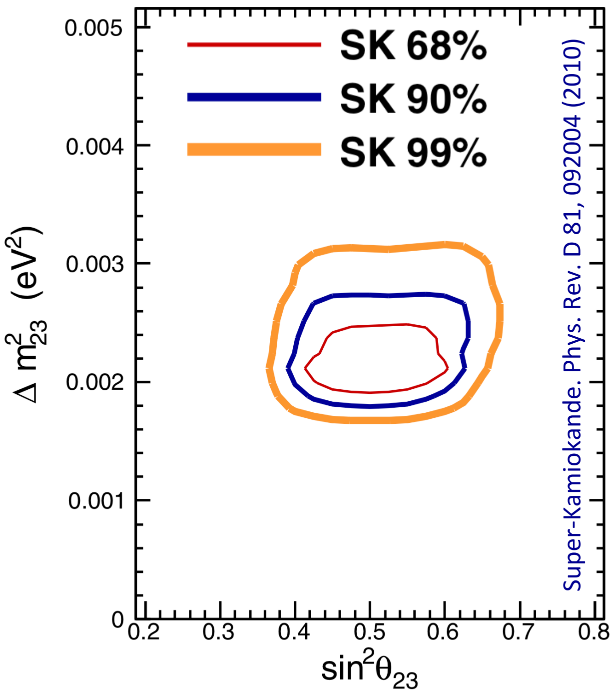


UPward-going **M**uons





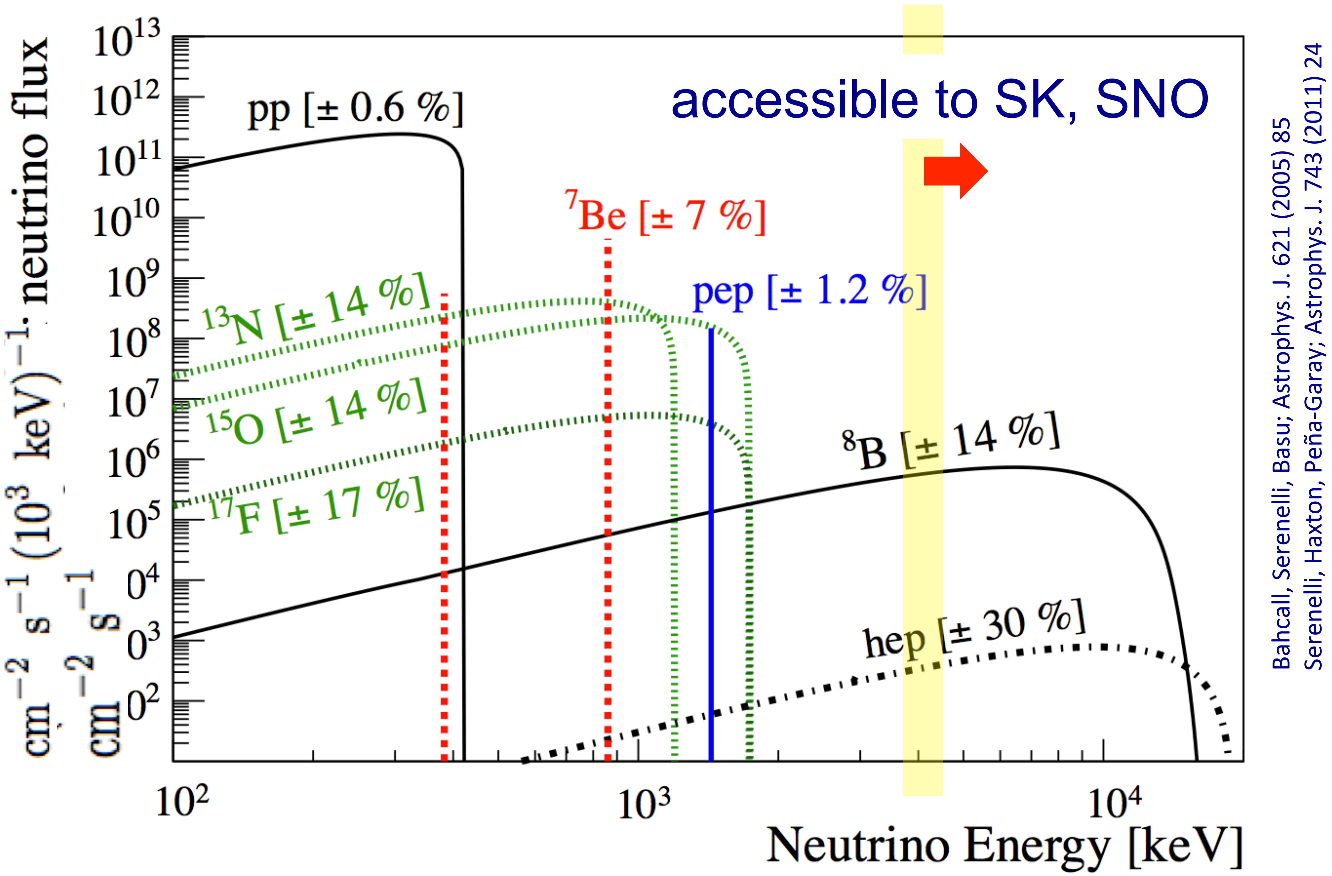




"a la":

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right),$$

Solar ν's



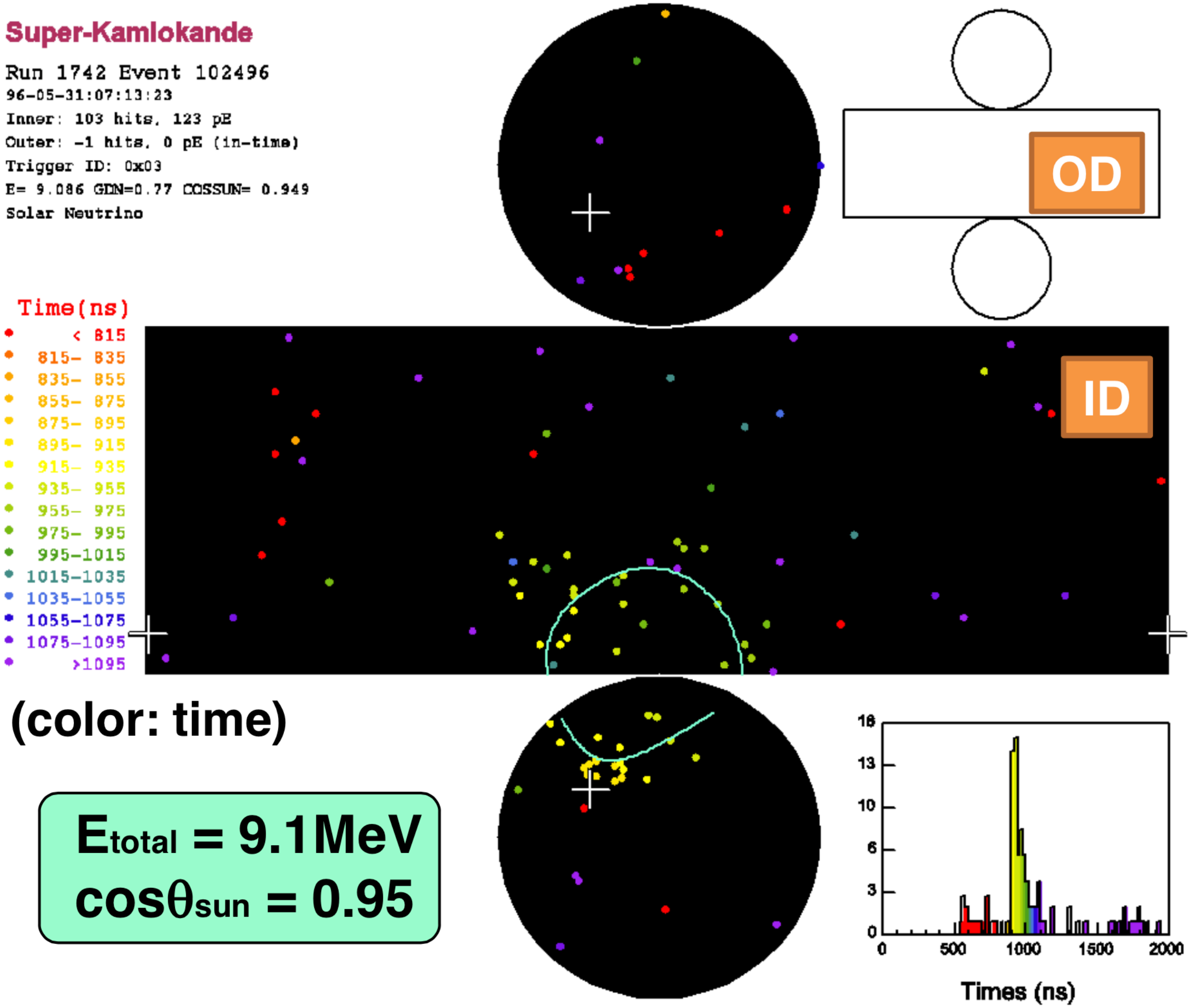
Very low energies:
Cl, Ga experiments. Very difficult, counting experiments

SK: precise measurement of [only] ν_e from elastic scattering

$$\nu + e \longrightarrow \nu + e$$

SNO: also NC → access to ν_e, ν_μ, ν_τ → **direct access to flavor oscillation**

Solar ν's



(color: time)

E_{total} = 9.1MeV
$\cos\theta_{sun}$ = 0.95

$\nu + e^- \rightarrow \nu + e^-$

Elastic scattering (ES) reaction is used for solar neutrinos

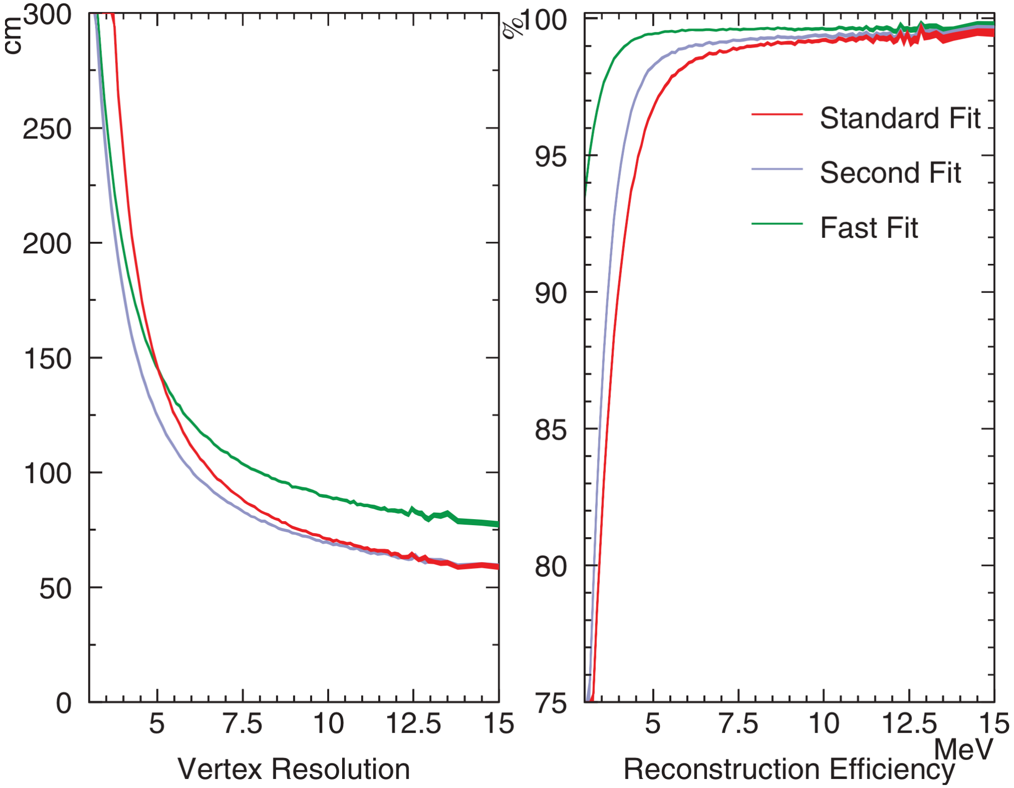
- Timing information ⇨ vertex position
- Ring pattern ⇨ direction
- Number of hit PMTs ⇨ energy

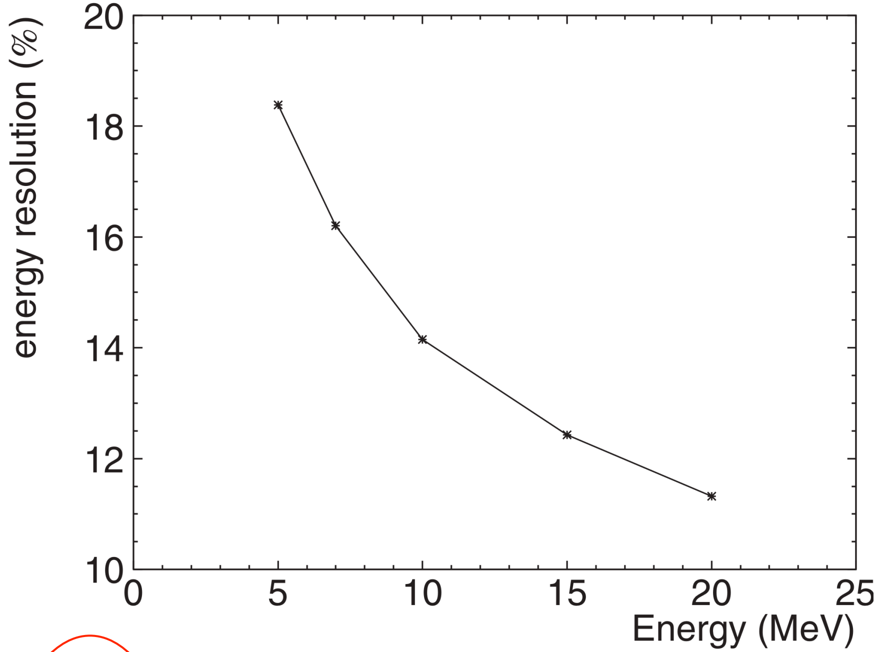
~6hit / MeV (SK-I, III, IV)

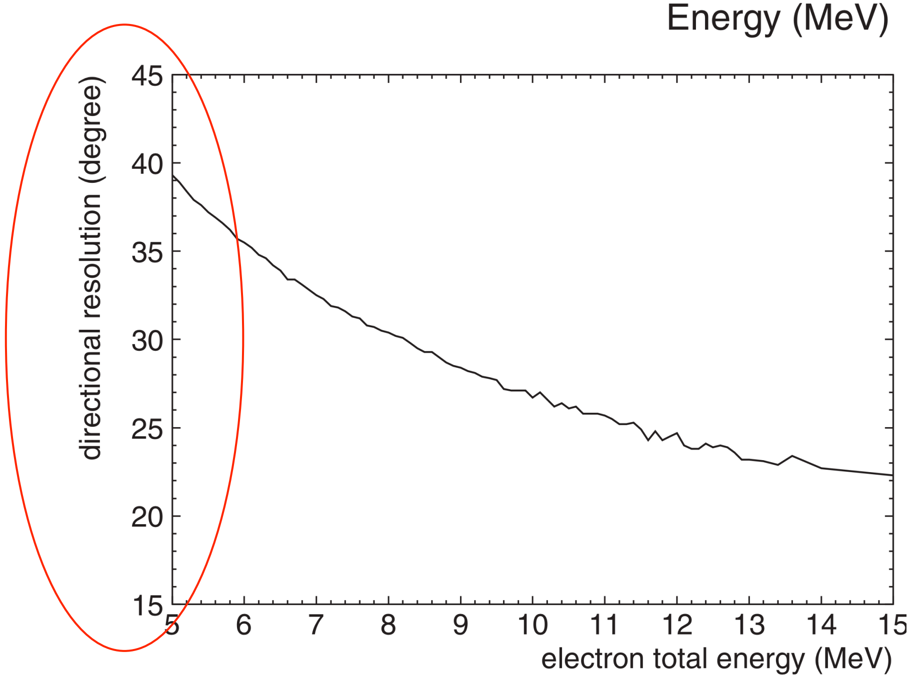
Nakahata: UAM 2012

Solar ν's reconstruction by Super-Kamiokande

$$\nu + e \longrightarrow \nu + e$$



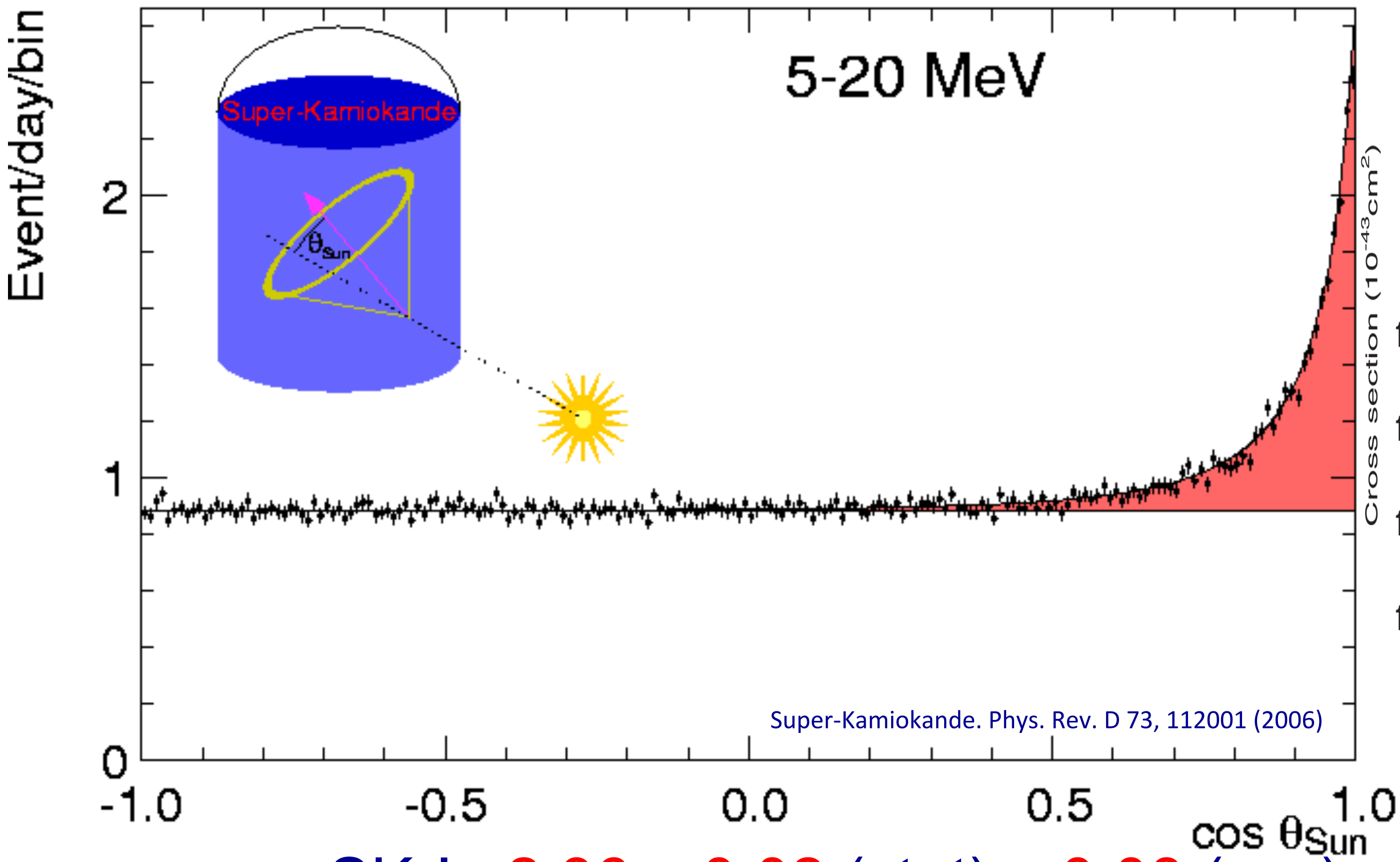




Super-Kamiokande. Phys. Rev. D 73, 112001 (2006)

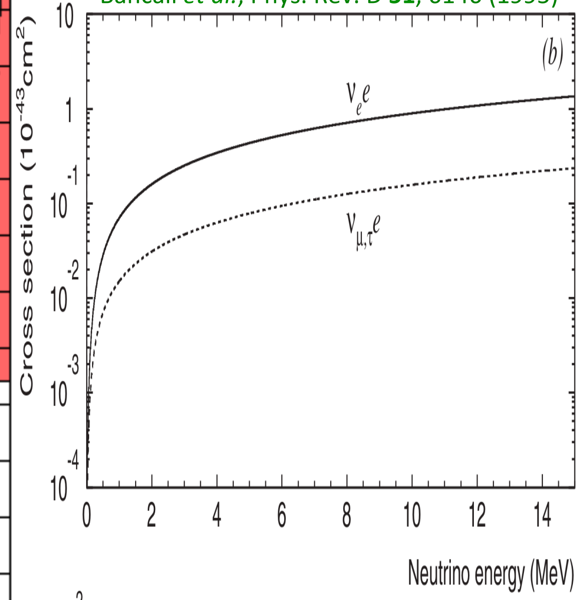
^{8}B solar ν flux by Super-Kamiokande

signal extracted from directional correlation of recoiling e^- with incident ν at ν - e^- scattering



Input: cross-section for ν - e^- elastic

Bahcall *et al.*, Phys. Rev. D **51**, 6146 (1995)



SK-I: 2.36 ± 0.02 (stat) ± 0.08 (sys) • 10^6 cm^{-2} s^{-1}

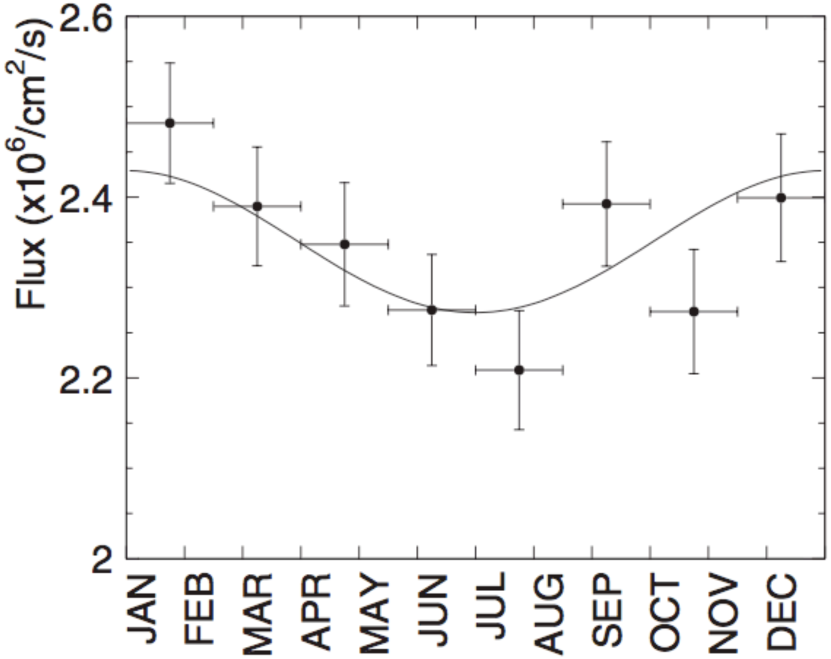
expected SSM: 5.79 • 10^6 cm^{-2} s^{-1}

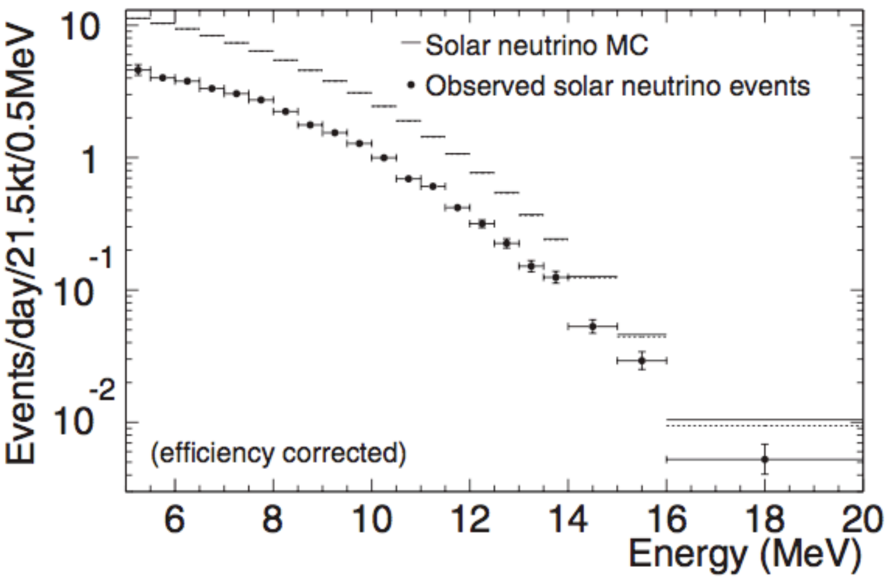
Bahcall, Pinsonneault; Phys. Rev. Lett. 92, 121302 (2004)

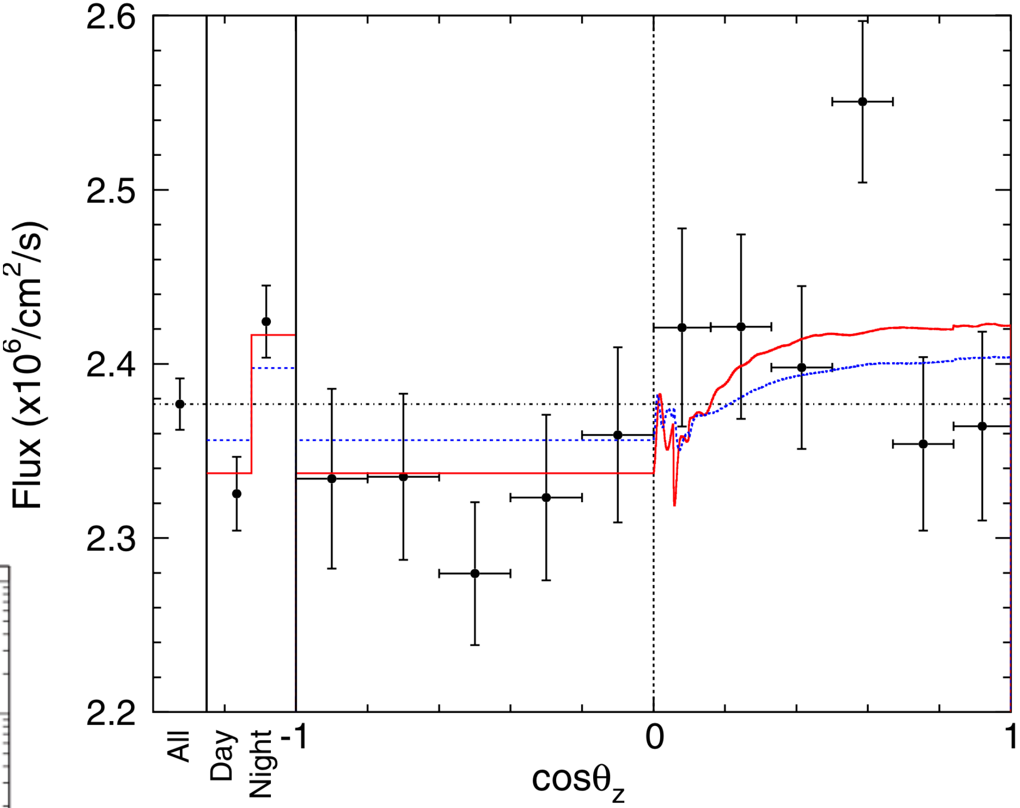
➔ Where are the missing of ν_e from the Sun ? Is SSM wrong ?

^{8}B solar ν flux by Super-Kamiokande; some other relevant results

PHYSICAL REVIEW D **73**, 112001 (2006)

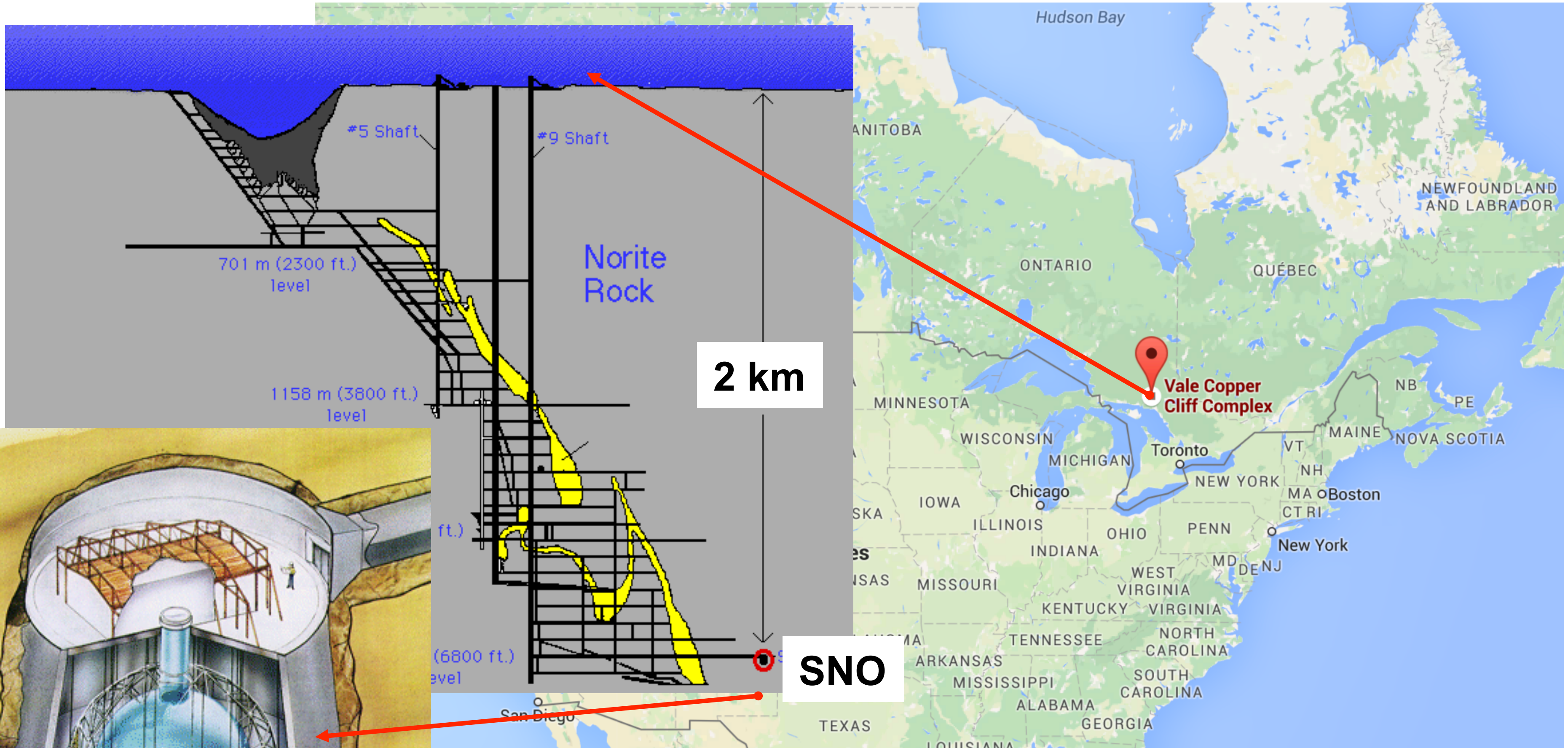


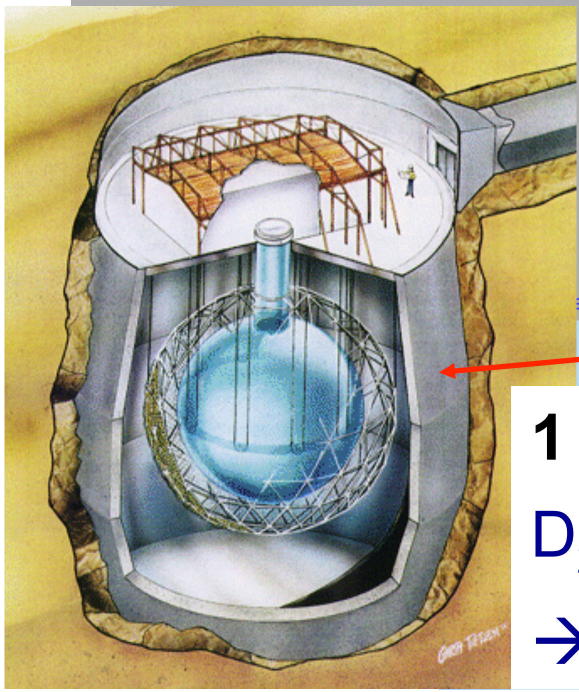




Super-Kamiokande. Phys. Rev. Lett. 112, 091805 (2014)

Sudbury Neutrino Observatory





1 k-ton heavy-water-Cherenkov detector

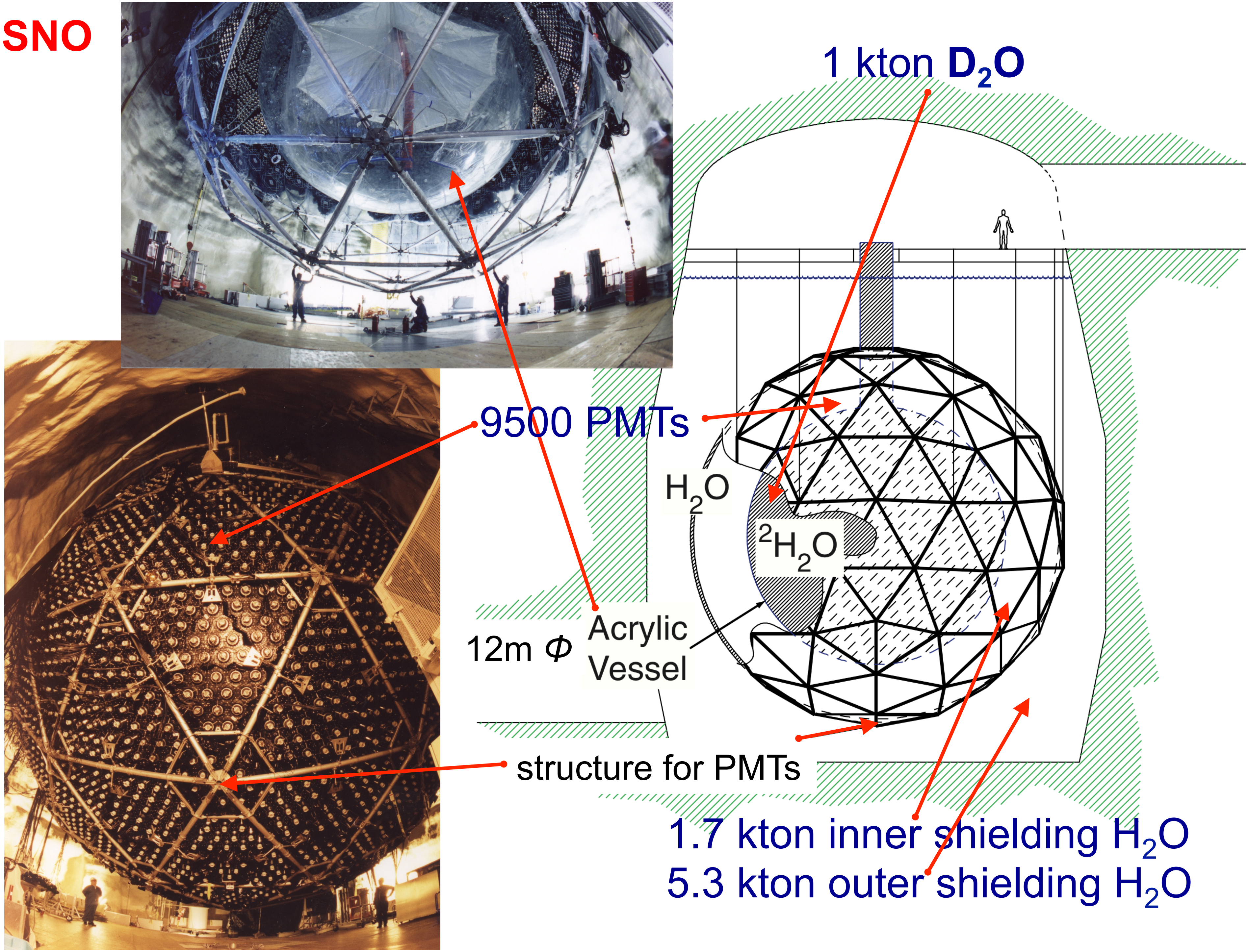
D_2O → access to NC, CC, ES ν interactions

→ Access to all three ν types: ν_e, ν_μ, ν_τ

➔ Access to the whole ν flux from the sun

Chen; Phys. Rev. Lett. 55, 1534 (1985)

SNO


1 kton D$_2$O
9500 PMTs
H$_2$O
^{2}H$_2$O
12m Φ
Acrylic Vessel
structure for PMTs
1.7 kton inner shielding H$_2$O
5.3 kton outer shielding H$_2$O

Main reactions at SNO

Elastic **S**cattering

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

sensitive to ν_e, ν_μ, ν_τ
but ν_μ, ν_τ suppressed by ~ 1/6,
similar as in Super-Kamiokande

Cerenkov ring; directionality

Charged **C**urrent scattering

$$\nu_e + d \rightarrow p + p + e^-$$

sensitive **only** to ν_e
(for solar ν energies)

Cerenkov ring; energy information

Neutral **C**urrent scattering

$$\nu_x + d \rightarrow p + n + \nu_x$$

sensitive to **all three** ν_e, ν_μ, ν_τ
with E[ν_x] > 2.2 MeV (binding E.)

neutron capture:

$^2H + n \rightarrow {}^3H + \gamma$ [6.2 MeV]

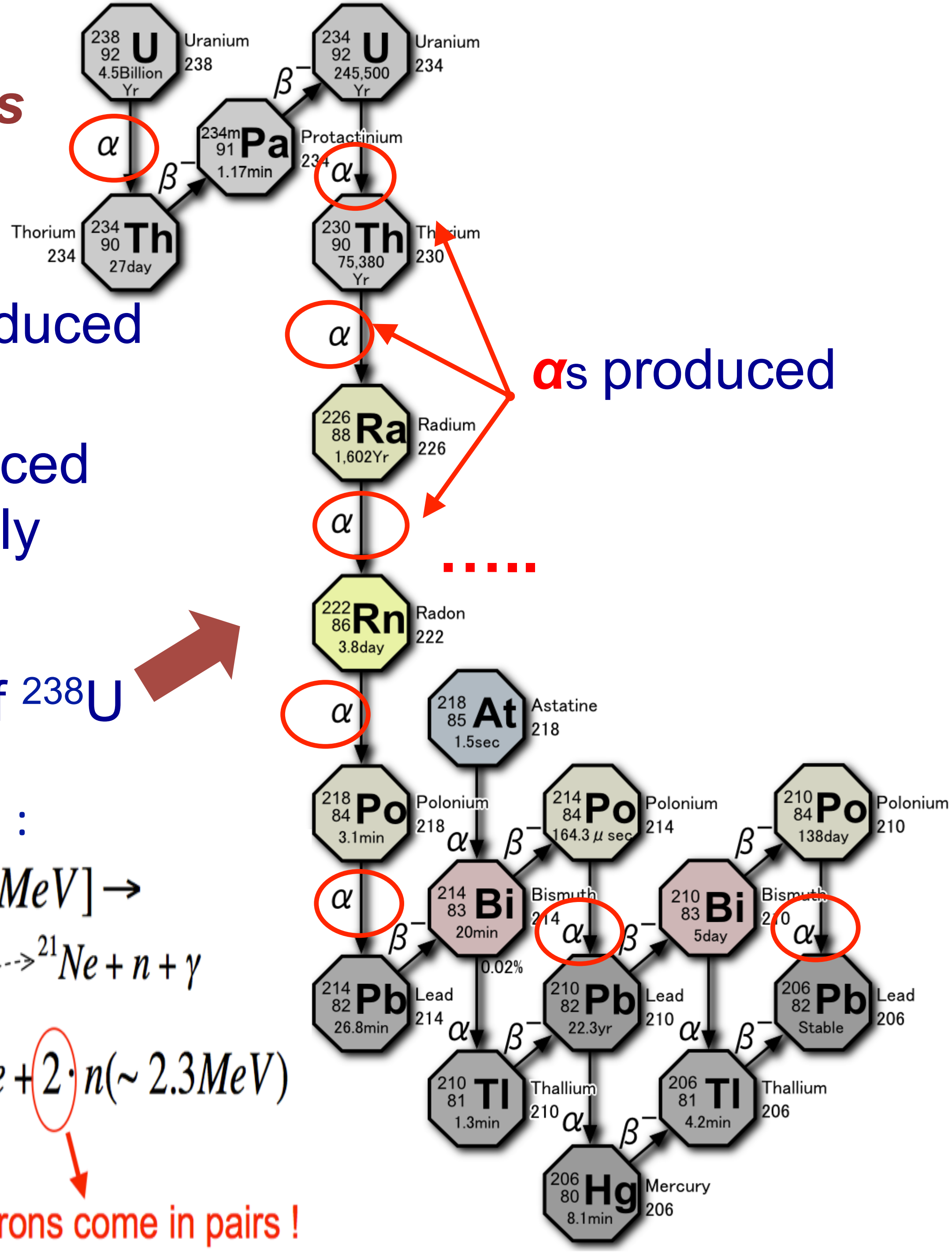
Cerenkov ring; just event counting

A very severe problem for NC is *background neutrons*

irreducible background
there are many naturally produced

for instance neutrons produced from ***α*** decays in the naturally present radioactive chains

for instance that of ^{238}U



the ***α***s interact with the water :

$$^{18}O + ^{4}\alpha(\sim 6MeV) \rightarrow ^{22}Ne^*[\sim 15MeV] \rightarrow$$

$$\text{X} \dashrightarrow ^{22}Ne + \gamma \qquad \text{X} \dashrightarrow ^{21}Ne + n + \gamma$$

$$\rightarrow ^{21}Ne^*[\sim 12.5MeV] + n(\sim 2.5MeV) \rightarrow ^{20}Ne + 2 \cdot n(\sim 2.3MeV)$$

neutrons come in pairs !

P. Fernández

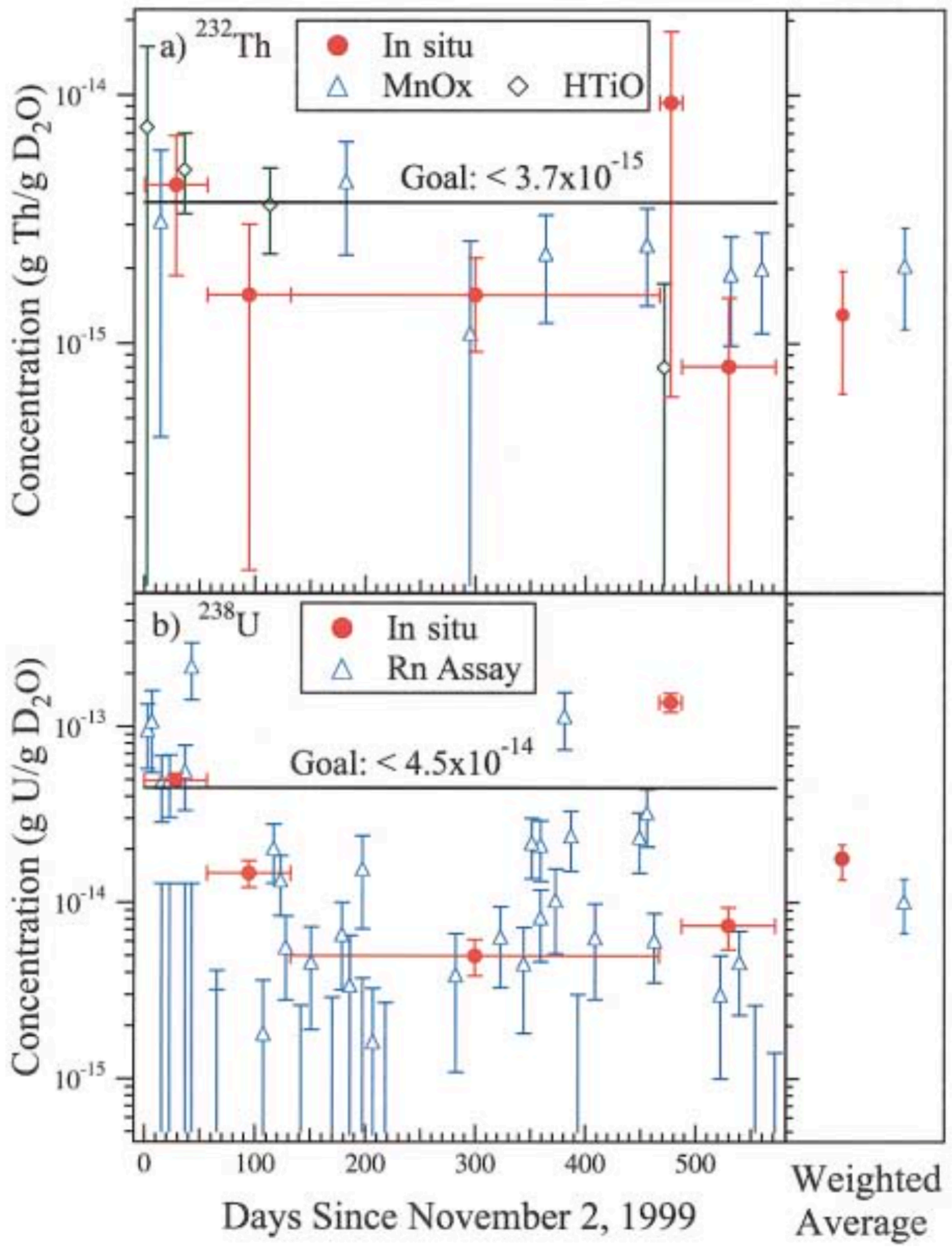
A very severe problem for NC is ***background neutrons***

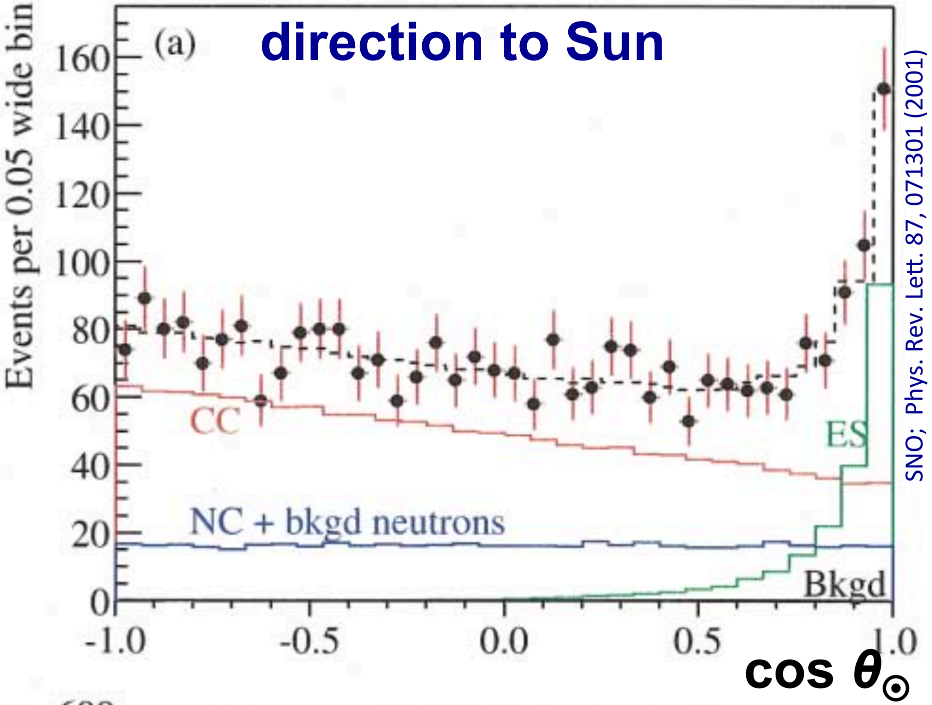
irreducible background →

a) minimize to the maximum
   - purest D_2O
   - acrylic vessel to isolate D_2O from external contamination

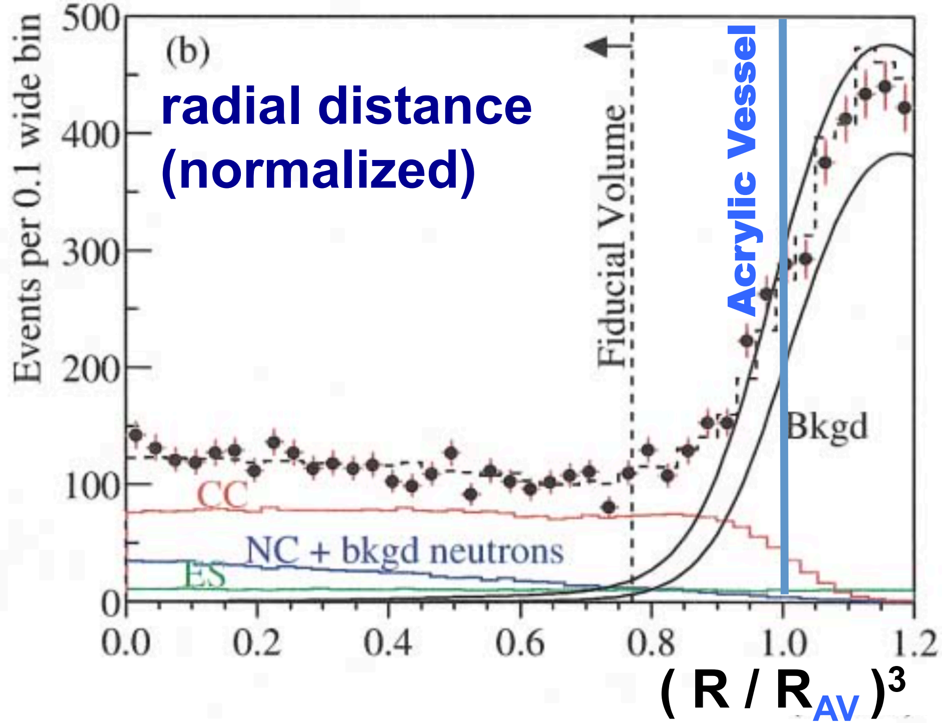
b) quantify to the highest precision:
   - permanent monitoring by
   - 2 ex-Situ radioactivity cont. meas. systems
   - 1 in-situ technique

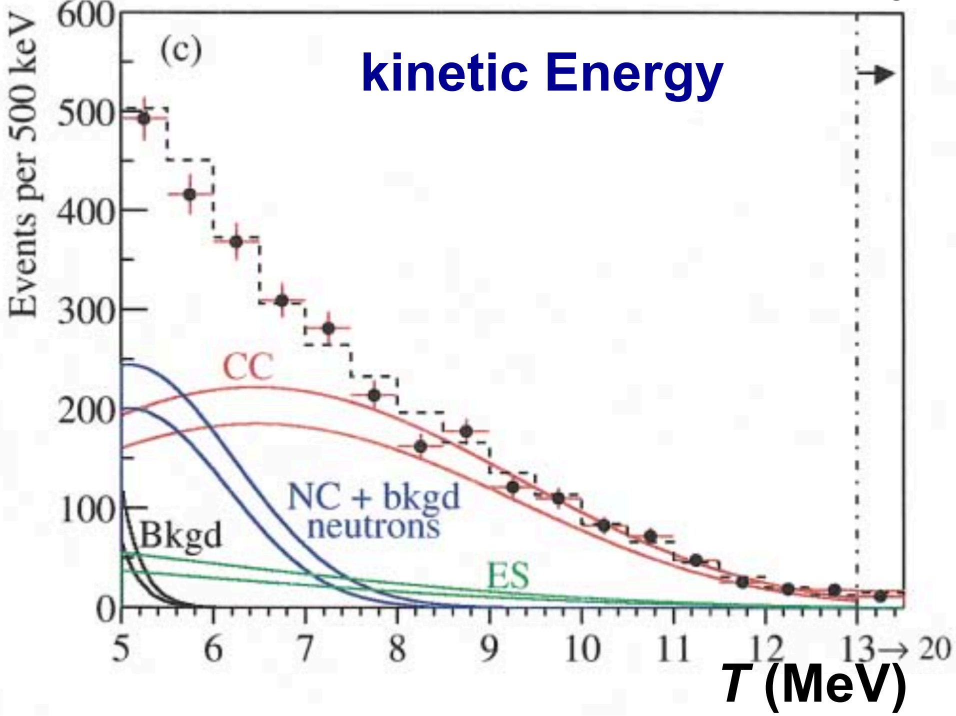
SNO; Phys. Rev. Lett. 89, 011301 (2002)





SNO; Phys. Rev. Lett. 87, 071301 (2001)
SNO; Phys. Rev. Lett. 89, 011301 (2002)

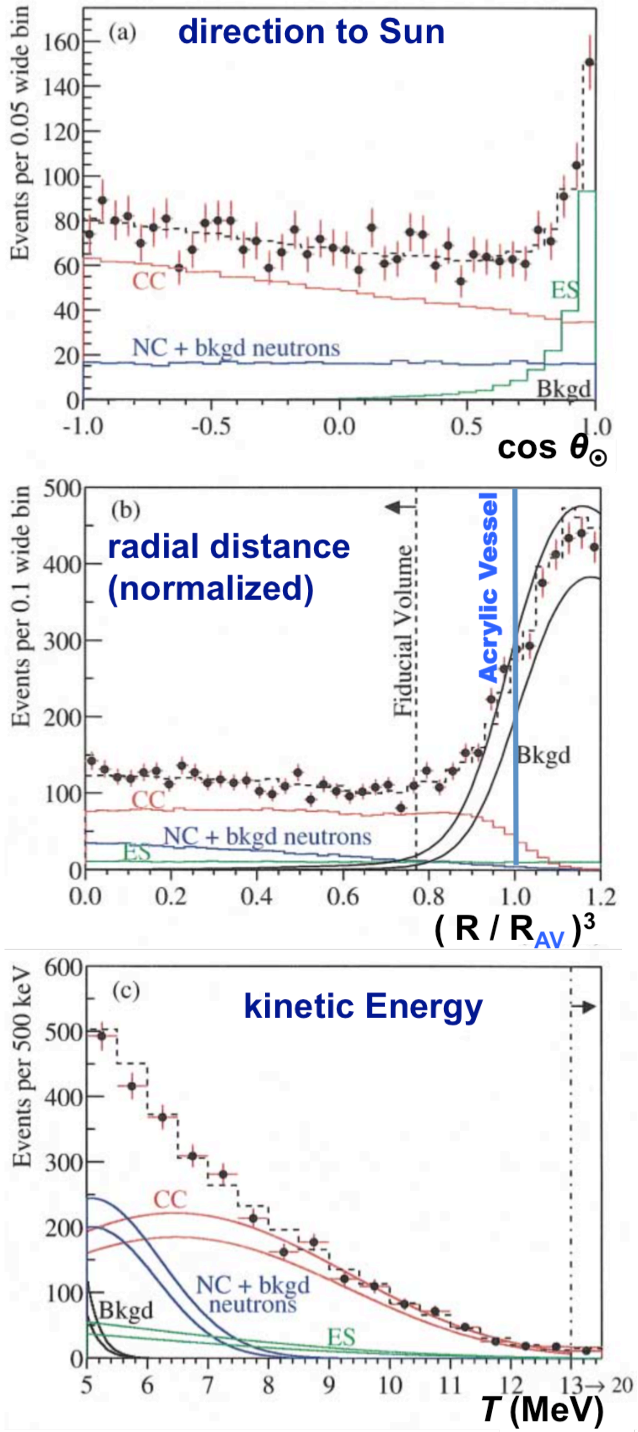




Fit measured flux to

$$\phi_{CC}\,[\,\cos\theta_\odot,\ (R / R_{AV})^3,\ T\,] +$$
$$\phi_{ES}\,[\,\cos\theta_\odot,\ (R / R_{AV})^3,\ T\,] +$$
$$\phi_{NC}\,[\,\cos\theta_\odot,\ (R / R_{AV})^3,\ T\,] +$$
$$\text{Bkgd}\,[\,\cos\theta_\odot,\ (R / R_{AV})^3,\ T\,]$$

using MC generated *pdf*s
assuming no flavor transformation
and ^{8}B spectral shape



Results: [• $10^6\ cm^{-2}s^{-1}$]

$$\phi_{CC}^{SNO} = 1.76^{+0.06}_{-0.05}(\text{stat})^{+0.09}_{-0.09}(\text{syst}),$$

$$\phi_{ES}^{SNO} = 2.39^{+0.24}_{-0.23}(\text{stat})^{+0.12}_{-0.12}(\text{syst}),$$

$$\phi_{NC}^{SNO} = 5.09^{+0.44}_{-0.43}(\text{stat})^{+0.46}_{-0.43}(\text{syst}).$$

SK-I [ES]: 2.36 ± 0.02 (stat) ± 0.08 (sys) ✓

expected SSM: 5.75 • $10^6\ cm^{-2}\ s^{-1}$

Bahcall, Pinsonneault; Phys. Rev. Lett. 92, 121302 (2004)

SNO; Phys. Rev. Lett. 87, 071301 (2001)
SNO; Phys. Rev. Lett. 89, 011301 (2002)

➔ There is no deficit of ν_e from the Sun w.r.t. the SSM, but they have **oscillated to** ν_μ, ν_τ in their way to the Earth ! ✓

Nobel 2015

ν_x fluxes are from a change of variables:

ϕ^{SNO}_{CC}, ϕ^{SN}_{ES}, ϕ^{SNO}_{NC} $\longrightarrow$ ϕ_e, ϕ_μ, ϕ_τ

$$\phi_e = 1.76^{+0.05}_{-0.05}(\text{stat})^{+0.09}_{-0.09}(\text{syst})$$

$$\phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}(\text{stat})^{+0.48}_{-0.45}(\text{syst})$$

Some final remarks

This is an enormous step forward in Science
… but certainly not the end

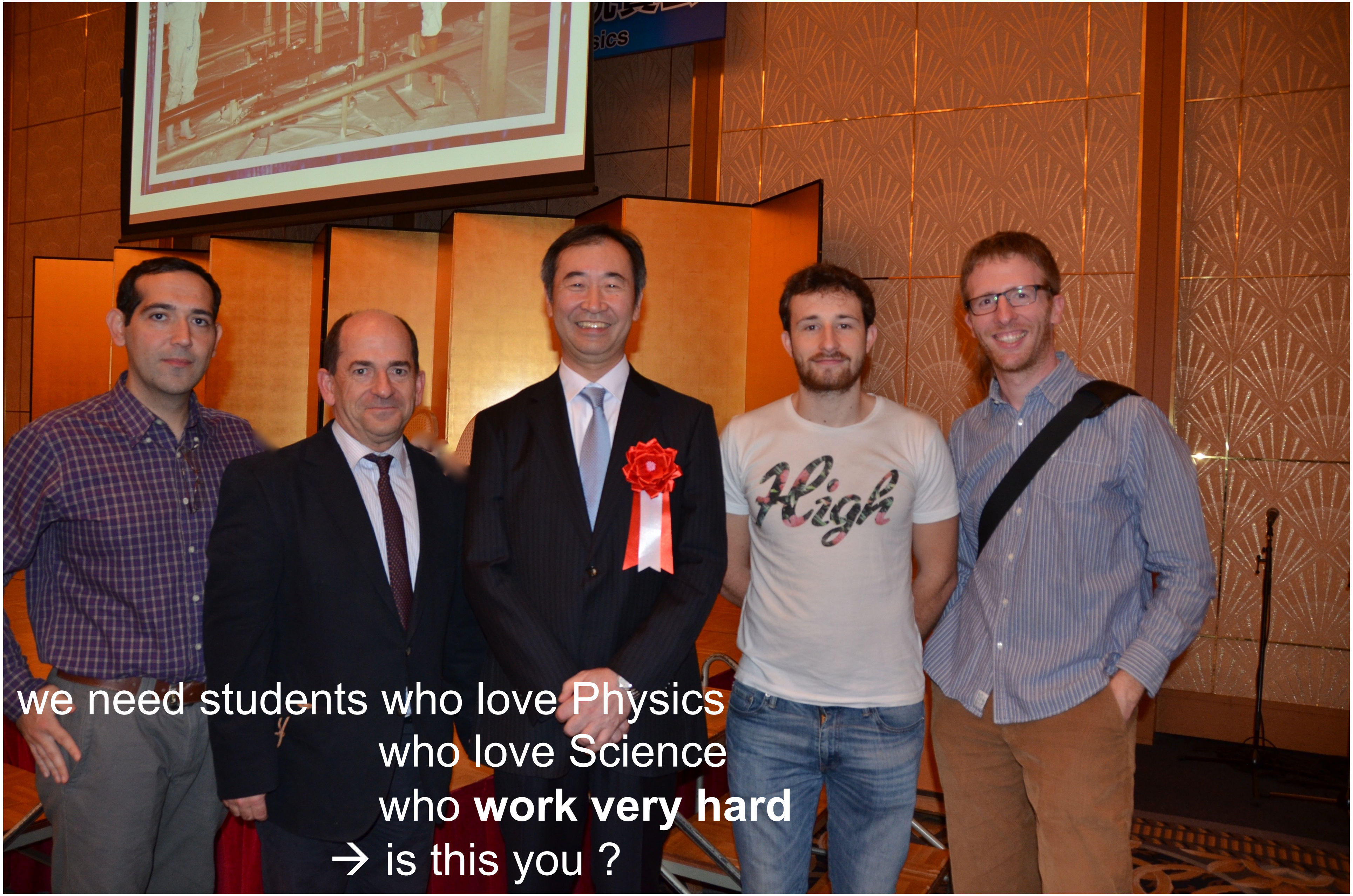
There is yet to discover / learn … basically everything in our process of understanding Nature

Some very important next related steps:

- CP violation in the leptonic sector
- Majorana / Dirac nature of neutrinos, sterile neutrinos
- Proton decay
- *High statistics/precision Neutrino astrophysics*

We (UAM) are very much involved in this research program:

- NEXT experiment at Canfranc Underground Lab.
- Super-Kamiokande at Kamioka Observatory
- Super-Kamiokande-Gadolinium
- Hyper-Kamiokande (~20 x SK) at Kamioka Observatory


High
we need students who love Physics
who love Science
who **work very hard**
→ is this you ?